THE UNIVERSITY OF ALBERTA

RELEASE FORM

NAME OF AUTHOR: [illegible]

TITLE OF THESIS: [illegible]

DEGREE FOR WHICH THESIS WAS PRESENTED: [illegible]

YEAR THIS DEGREE GRANTED: [illegible]

Permission is hereby granted to THE UNIVERSITY OF ALBERTA LIBRARY to reproduce single copies of this thesis and to lend or sell such copies for private, scholarly or scientific research purposes only.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

(Signed) [illegible]

PERMANENT ADDRESS:

[illegible]

DATED [illegible]

THE UNIVERSITY OF ALBERTA

GROUNDWATER APPRAISAL OF THE FYLDE AREA, LANCASHIRE

by

© JAMES E.K. MULIIRA B.Sc.

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

EDMONTON, ALBERTA

FALL, 1978

ABSTRACT

This report presents an evaluation of the geology, hydrogeology and groundwater chemistry of the Fylde area, Lancashire, England. Permian and Triassic bedrock is mantled by up to 140 feet of glacial deposits. One major bedrock aquifer, the Bunter Sandstone, has been defined.

This unit has average saturated thickness ranging from 30 to 65 feet. A transmissivity of 10,572 igpd/feet was calculated from a three-day pump test at a locality where the saturated thickness was 37 feet. Using the same test results a 20-year safe yield of 111 igpm was calculated. The actual safe yield value, however, could be smaller in view of the relatively low pumping rate used during the test (60 igpm). Bail tests were conducted both in the northern and southern sections of the aquifer. These gave an indication that relatively low yields can be expected.

The Calder Hills (Fells) which extend into the Pennines to the east, are thought to be areas of recharge. Groundwater quality is best in these areas and deteriorates gradually towards the west coast as the concentration of cations and anions gradually increase. Generally, groundwater from the Bunter Sandstone has total solids ranging from 200 to 800 parts per million. In a few localities, however, water with total solids content higher than 1000 ppm has been encountered (largely in discharge and saltmarsh areas).

Well defined chemical patterns and a downstream salinity increase are thought to be produced either by mineral dissolution or megascopic dispersion effects. Unfortunately, there are insufficient data available to choose between the two. Except for the locally high nitrate and iron concentrations, the water is good quality.

ACKNOWLEDGEMENTS

The writer is grateful to the Canadian International Development Agency for the assistance received. He also wishes to acknowledge Dr. F.W. Schwartz, for invaluable advice and guidance. Members of staff of the Departments of Geological Sciences and Civil Engineering, University of Birmingham, particularly Dr. R. Pickering and Dr. Rutaro-Mutoro assisted in the project and reviewed the manuscript. Additional assistance was provided by: Personnel of the British Institute of Geological Sciences - Leeds and London Offices; personnel of the Ribble and Rivers Division of the North-West Water Authority of the United Kingdom and authorities of the Department of the Environment - Water and Air-photograph Units, respectively.

The author is also indebted to Mr. J. Payne for assisting in laboratory analyses, Mr. H. Clifford for providing drawing and photographic facilities and Mrs. J. Theander, who ably typed the final draft. Special thanks is expressed to the writer's wife, Margaret, for her patience, moral support and assistance in drafting some of the figures.

TABLE OF CONTENTS

Chapter | Page

LIST OF TABLES

LIST OF FIGURES

LIST OF ENCLOSURES

CHAPTER I

INTRODUCTION

Location and Extent of Area

The study area consists of part of the district of Lancashire, located in northwest England (Figure 1). It lies between the estuaries of the river Wyre in the north and river Ribble in the south. The Irish Sea forms its western boundary and the upland county of Bowland roughly marks the eastern boundary. The study area covers approximately 212 square miles. It is bounded by latitudes of 53° 42' and 53° 54' north, and by longitudes 2° 44' and 3° 03' west.

Purpose and Scope of Investigation

The purpose of this study was to describe quantitatively, the hydrogeological setting of the thick water-bearing sandstone in the Fylde area, to map transmissivity distributions and to investigate the movement and hydrochemistry of groundwater. It is hoped that this information will contribute towards a better understanding of the sandstone aquifer, particularly with respect to the role that this formation plays in the integrated water resources of this region.

The scope of the investigation includes the

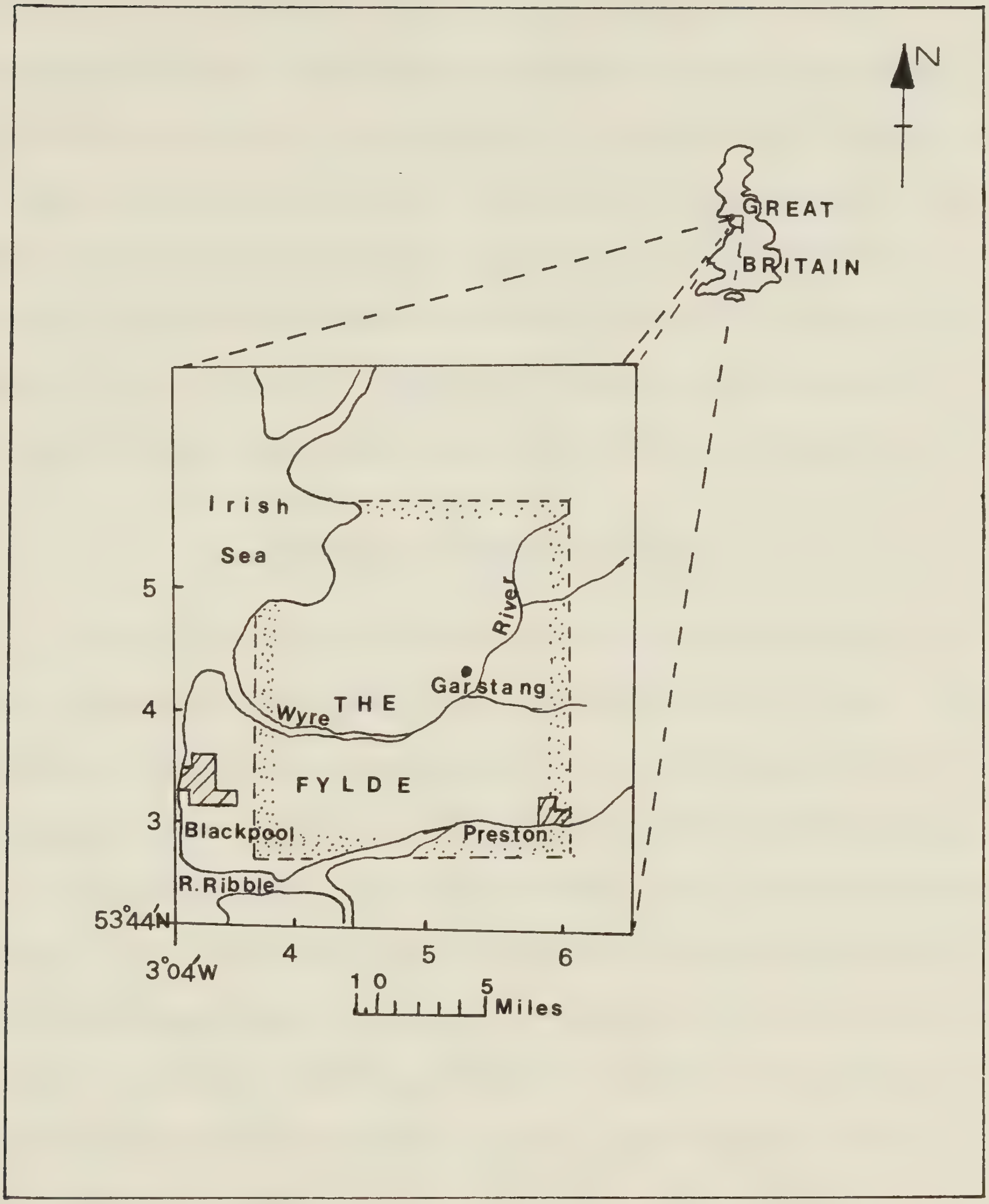


FIGURE 1

Map Showing Location of the Area

determination of the bedrock geology and transmissivity of the Bunter Sandstone, by aquifer testing methods. The increasing development of sandstone aquifers in Great Britain, particularly within the Permian and Triassic formations, makes it of continuing importance to collate and assess, as much information as possible relating to the lateral and vertical extent of important aquifer systems, their potential, continuity and structure, possible sources of recharge, variations in formation characteristics and variations in the chemical quality of the groundwater.

Previous Investigations

Several geologically oriented investigations in northern England have provided useful though limited information concerning the geology of the Fylde and the surrounding area (Edward and Trotter, 1954, Worthington, 1972). Although the works are not directly concerned with the Fylde, they are important because the stratigraphic terminology used here is based, in part, on information contained in these investigations. They have also been the source of useful basic hydrological, geochemical and paleontological data.

The earliest published geological work concerning the area was by D.A. Wray (1936), who conducted geological mapping of the Pennines and the adjacent areas, including the Fylde. Edward and Trotter (1954), while improving on Wray's work, later studied the distribution of Carboniferous

and Permian deposits in the area. Investigations into the permeability of sandstone in the study area have been conducted by Worthington, et al. (1972, 1973, 1975) and by Crook and Howell (1970a, 1970b).

Methods of Study

A review of the data collected during previous investigations indicated that additional information, especially quantitative data, was necessary for this investigation. These data were collected during one and half summer field seasons (1976-1977), an autumn field trip (October-November, 1976) and a Spring/Summer field trip (1977).

The geologic interpretation in this study were based on reports of the British Institute of Geological Sciences, geological and soil maps (Edward and Trotter, 1954), and studies conducted during this investigation. The lithology of most formations discussed in this report was determined mainly through examination of samples from test holes and wells. The area is almost entirely covered by glacial drift. An examination of the drill cuttings from water wells, test holes, information from drillers' logs and published reports provided the basis for developing a detailed stratigraphy.

Data on hydraulic properties of the aquifer were obtained from:

1. production data recorded on drillers' logs, and registered municipal wells,

2. pumping tests,
3. bail tests and,
4. water level measurements.

Pumping tests were conducted by the author as part of the program of study. They consisted of step-drawdown, constant withdrawal and bail tests. Discharge rates in excess of 60 imperial gallons per minute (igpm) were measured with a graduated 45 gallon drum. Static water levels and water levels after bailing were determined with an electric water level indicator.

Water samples from the Bunter Sandstone were analyzed both in the field and laboratory. In all cases, wells were pumped until temperature stabilized to that of the aquifer in order to insure that samples were apparently representative of the aquifer.

Some water samples were analyzed by the author. The analyses carried out by the water authorities in Birmingham served as a control for assessing the accuracy of the field determinations made by the author.

Detailed lithologies of rock samples were examined in the laboratory at the Department of Geological Sciences, University of Birmingham. Samples were studied using a binocular microscope and described using terminology modified by Folk (1959). The grain size terminology used is from the Udden-Wentworth scale, by Lane, et al., (1947).

CHAPTER II

PHYSICAL GEOGRAPHY

Topography

The area is one of lightly marked geomorphic transition. The western half of the Fylde occupies the south-western flood plains and coastal flats of the district of Lancashire. The relief of the north-eastern, central and eastern areas is gently undulating, ranging from 50 to 400 feet above sea level. Further to the east, however, relief becomes more pronounced as the high plateaux of the Pennines are approached.

Drainage Basins

The study area occupies a portion of two significant drainage basins; the Wyre river basin and the Ribble river basin (Figure 2). The majority of map area is drained by these two river systems which ultimately discharge into the Irish Sea. The size of the Wyre river basin is marginally smaller and it is less developed than the Ribble river basin.

Climate

The Fylde has the typical mild climate (Figure 3) of the western seaboard of Britain. The mean temperature of Blackpool for February, the coolest month (39.9°F.) is higher

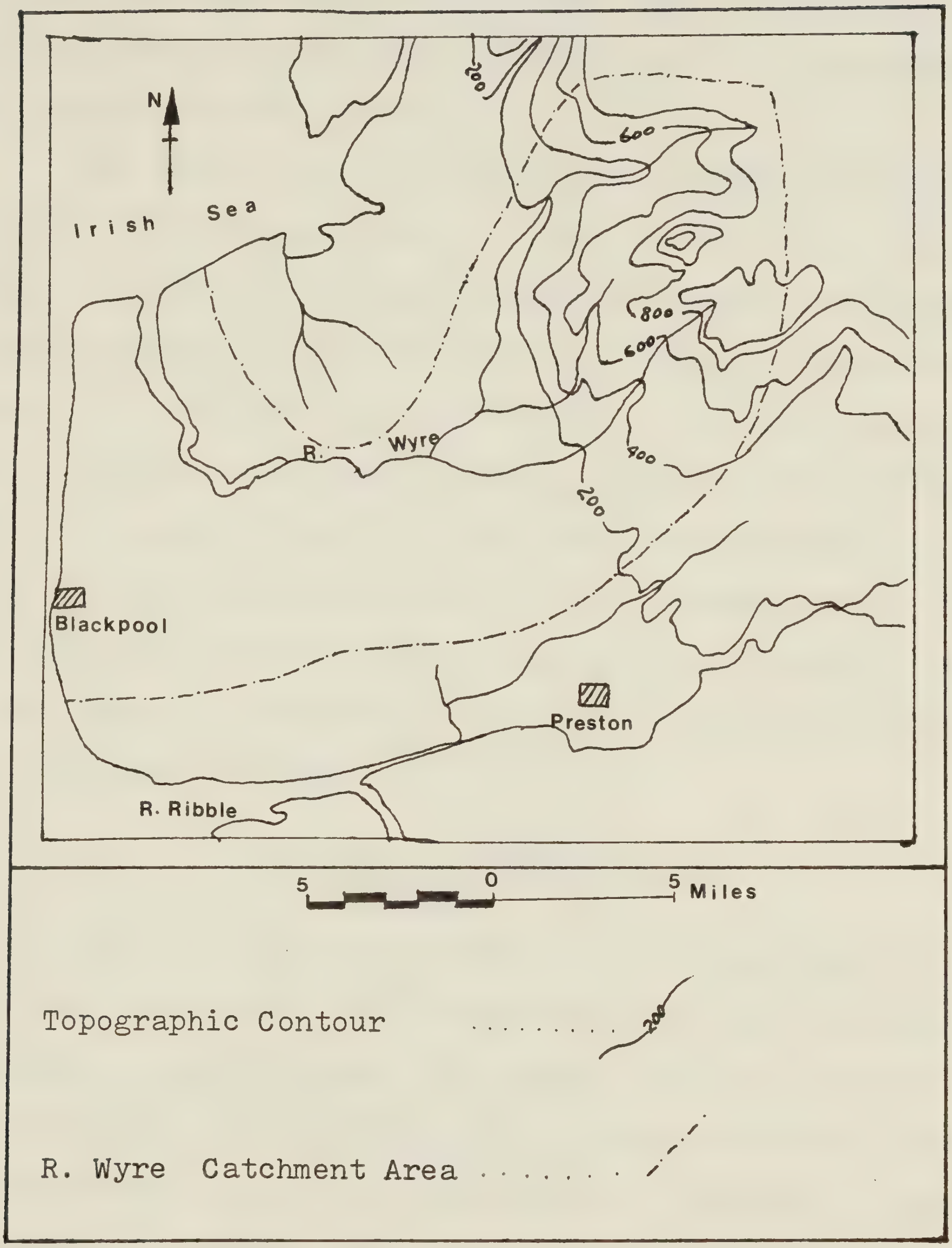


FIGURE 2

Generalized Topography and Drainage Basin Map
of the Fylde and Surrounding Areas

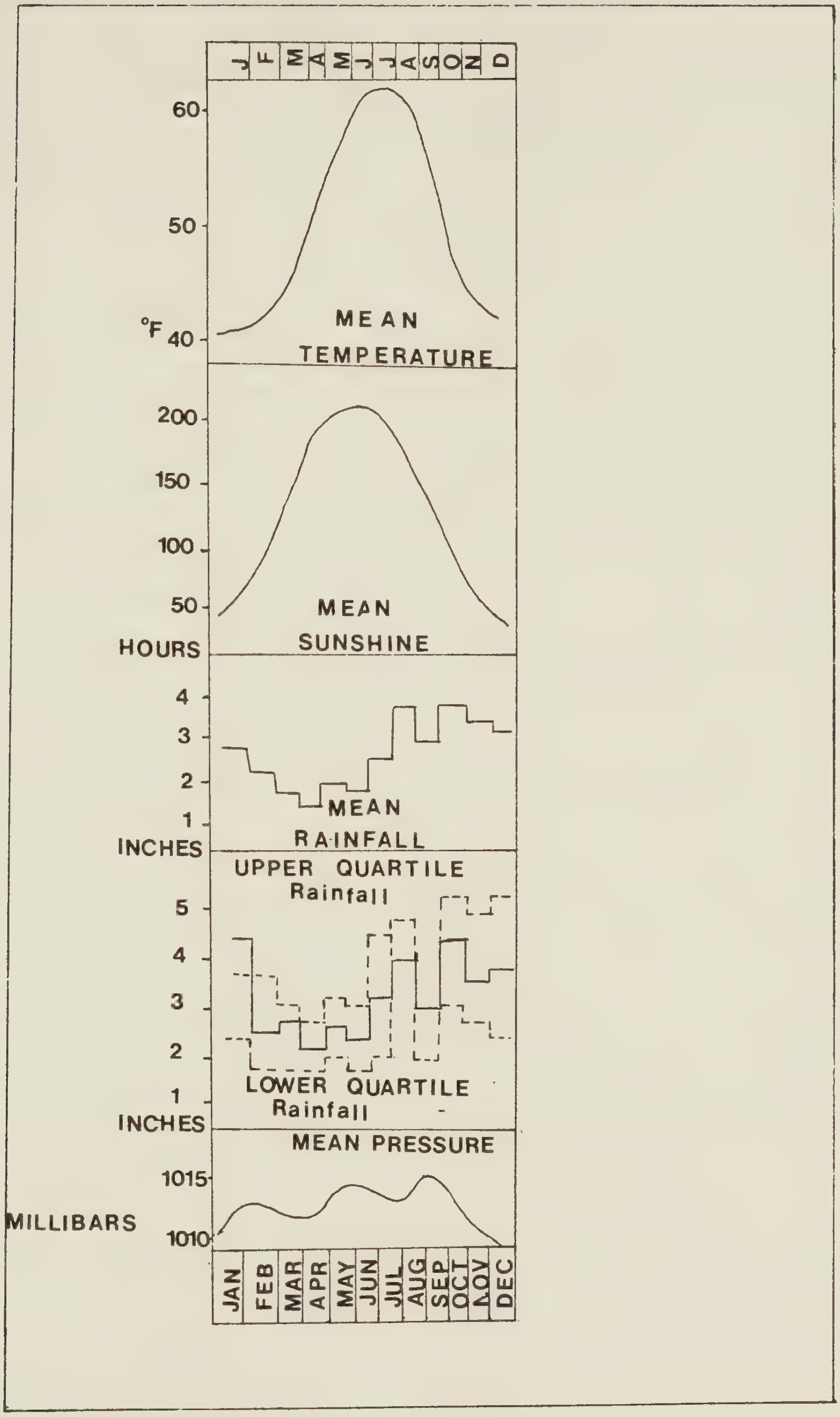
than that on the east coast, but lower than that in North Wales or the South Western Peninsula. Snow rarely lies on the ground for more than two or three days and occasionally none falls during the winter.

The Fylde has a relatively low rainfall for the west coast of Britain. The lowest rainfall of the whole western seaboard are observed in the rainshadow behind North Wales. Rainfall gradually increases northward along the Lancashire coast; it is two to three inches more at Liverpool than in the Dee Estuary, and three to four inches more at Blackpool than at Liverpool. But the mean rainfall at Blackpool for the 35 year period is only 35.67 inches, compared with the postulated 40 inches as the average general rainfall of the British Isles. A summary of the climatic elements of the Fylde, is shown in Figure 3.

Industry and Accessibility

The Fylde area is renowned for its dairy and subsidiary industries, with large Friesian herds on farms. Proximity to large markets has greatly stimulated production from arable and pasture land alike. Among the major demands on groundwater supplies in the area are irrigation, livestock and water for domestic utilization in the expanding cities of Blackpool and Preston.

Blackpool, the regional seat, is accessible from all land directions by major hard-surfaced highways and by freight railway lines. Well maintained gravel roads define almost



Source of data: British Midland Meteorological Office, Edgabaston,
Birmingham

FIGURE 3

Climatic Elements of the Fylde, Lancashire

every section line in the area.

CHAPTER III

REGIONAL GEOLOGY

Introduction

Understanding the geologic evolution of the geology of the area is essential for better understanding of hydrogeologic properties. In the Fylde area, important aquifers are restricted to the Permian and Triassic formations. Other units are of low permeability.

The bedrock is mostly covered by surficial deposits and vegetation. Outcrops in the Fylde area are very scarce, hence surface geologic mapping of the area has been limited.

The stratigraphic nomenclature used in this report conforms as nearly as possible with the British code of stratigraphic nomenclature (Wright, 1952). Rock stratigraphic terminology is that of D.A. Wray (1948) modified by W. Edwards and F. Trotter (1954), and W. Owen (1965).

Carboniferous, Permian and Triassic formations that underlie the map area are shown in Table 1 and these formations are discussed separately in the following sections.

General Features of the Carboniferous System

The existence of pre-Carboniferous rocks in the study area has not been proved; boreholes to 998 feet have not

TABLE 1

Table of Formations

Era	Period or Epoch	Rock Unit	Thickness (feet)	Lithology
QUATERNARY	Recent		0-100	River alluvium, blown sand, alluvial fans; flood plains; sands and silts
	and		0-250	Upper till, middle sand, lower till and; clay and glacial fluvial sand; silts
	Pleistocene			
MESOZOIC	Triassic	Keuper Marl	700-1000	Mudstones, sandstones, mottle sands, sands and gravel lenses
		Bunter Sandstone	3000	Upper mottled sandstones, gravel Bunter pebble beds, lower mottled sandstones, fine, soft sandstones
PALAEZOIC	Permian	Upper Permian Marl Middle Permian Marl Lower Permian Marl		Silts, mudstones, dark red sands
	Carboniferous	Upper Carboniferous	5000	Coal measures. Limestone, Millstone and grit
		Lower Carboniferous	6000	

(Modified from: Edward and Trotter, 1954).

penetrated rocks of Devonian age.

Strata of Carboniferous age occur in the map-area almost entirely in the subsurface. These deposits, however, outcrop in many areas in the Pennines Uplands to the east. On the basis of lithology, the Carboniferous system is subdivided into Upper and Lower systems. A discussion of the Upper system is considered adequate since the Lower system is not well represented.

The upper Carboniferous system is made up of coal measures and Millstone Grit Series. This later unit is a sequence of mudstone and shale with light beds of sandstone and grit. It underlies part of the eastern half of the study area and extends, with increasing thickness, further east where an approximate thickness of 500 feet has been recorded (Edwards and Trotter, 1954). The two major subdivisions of the Carboniferous system represent successive phases of deposition in an area which was subsiding irregularly and in which sedimentation kept rough pace with subsidence.

In the map-area and the surrounding regions, there was a dominant initial period of clear water in which limestone was formed. Uplift of the neighbouring regions, to the east and north particularly, led earlier recurrent invasions of deltaic sediments, hence a characteristic succession of mudstone which overlies the Millstone Grits.

Triassic System

Triassic rocks are widely deposited over the study area. Because the exposures in the area of investigation are

very scarce, the subsurface findings are chiefly restricted to the Triassic rocks.

The Triassic sequence has been subdivided into two lithostratigraphic groups, the Bunter Sandstone and the Keuper Marl. These two formations will be discussed separately in the following sections.

Bunter Sandstone Formation

The most important aquifer in the Fylde area is the Bunter Sandstone. A thickness of up to 830 feet of this formation has been proved and its maximum thickness is much more. Most of the profiles show this unit to be comprised of soft red and mottled sandstone, with occasional beds of white pebble sandstones near the top of the sequence. Too little information is available to ascribe stratigraphical significance to this variation.

Earlier research workers in the area (Edwards and Trotter, 1954) distinguished two divisions of the Bunter Sandstone Formation: the sandstone above and below the pebble beds commonly referred to as the upper and lower mottled sandstones, respectively.

The lower sandstone is chiefly a fine-grained, soft sandstone, usually bright red in colour and occasionally mottled with yellow and white patches. Some loosely compacted layers contain worn sand grains, including the well-rounded 'millet seed' sands. This bed is well developed in the southern section of the study area, where it passes into

Permian beds.

Bunter pebble beds are generally coarser grained than the beds above and below them, and are of a more yellow or buff colour. These beds are distinguished by the presence of well worn pebbles and cobbles up to seven inches long. The most abundant rocks in these beds are coloured quartzites, and yellow, white and pink quartz veins; occasional pebbles of granite, mica-schist, chert and sandstone have been observed, and some of these were found to contain fossils of Carboniferous and earlier ages. Towards the north the sandstone becomes thicker, but the pebbles dwindle in size and in abundance, as if derived from some southern region.

Overlying the Bunter pebble beds is the upper sandstone. The latter is a fine-grained rock. Its degree of cementation is variable. It can easily be distinguished from the lower mottled sandstone. The grains of the upper sandstone are rounded, showing that the sandstone was water deposited. The Bunter Sandstone formation is overlain by the Keuper Marl.

Keuper Marl Formation

This rock is not a true marl since it contains less than ten per cent calcium carbonate and is really a dark red mud. Within the map area, the "Marl" has thin bands and patches of greenish hue, but it also includes (e.g. near Blackpool) thin bands of fine-grained sandstone which are often dolomitic. The Keuper Marl is characterized by

distinctive physical properties. Some of these are that it is brittle, fractures into small blocks, is a very fine-grained material and thus, has a low hydraulic conductivity.

The geological map of the area (Enclosure 8) shows the Bunter Sandstone aquifer as a sharply defined area with its boundaries which consist of major faults. Borehole information correctly located the Keuper Marl at great depth, not far from the western edge of the Bunter aquifer and thus it was deduced that the western boundary was faulted (Memoirs, 1929). Similarly, it was also concluded that the eastern boundary of the aquifer was extensively faulted. This investigation has shown that the eastern boundary was not correctly defined. Borehole data (BH. No. T46, Appendix I), reveal that a substantial thickness of Bunter Sandstone exists further to the north east than the present position of the presumed boundary of the aquifer. The adjusted position of the boundary is shown on Enclosures 4 and 5.

The extension of the 'Marl' eastwards into the Bunter Sandstone as seen from the western boundary of the sandstone may have resulted from the erosion of the sandstone to form a valley by a large river draining the Carboniferous highlands during the late Paleozoic Era.

Bedrock Topography and Drift Thickness

Maps showing the thickness of drift and the depth to bedrock are presented in Enclosures 2 and 3, respectively. These maps were constructed only in those parts of the area

where control was sufficient. According to the Isopach Map (Enclosure 2), the thickness of the drift varies from less than 25 feet to over 75 feet. The greatest thickness of the drift is found within buried valleys.

The Bedrock Topography Map (Enclosure 3) shows that the depth to bedrock sharply increases from east to the west. The elevations vary from less than ten feet (south east of Garstang) to over one hundred feet (near the Great Eccleston on the Wyre).

Quaternary Deposits

Pleistocene and Recent deposits cover nearly the entire area of study. The units are glacial till-clay, sand, gravel and assorted deposits of the recent post-glacial or Holocene period. The sequence can be subdivided into three main units called the lower till, the middle sands and the upper till. These units were all exposed in the coastal section in the past (Evans, 1975), but are now obscured. Within the area, the glacial till confines or partially confines the Bunter Sandstone.

The lower till is heavily compacted, purple-grey in colour and contains many small, highly polished and scratched erratics of Cumbrian and Scottish provenance, together with abundant comminuted shell debris. The upper till is brown to blue-grey and is noticeably more sandy and less compact in texture. Separating these two members is a thin unit of glacial sand (ten to thirty feet thick). Local undulations in

its surface are partially reduced by the cover of upper till, and are responsible for much of the topography in the eastern and southern sections of the study area. The lower till is believed to be a lodgement till and the upper one to represent englacial debris (Kingsley, 1975).

In the northern half of the area the glacial deposits have been trimmed over much of the lower ground by marine erosion but a nest of large drumlins rises through the later Flaudrian deposits. Over much of the low ground in the north and extreme south west, the glacial deposits are overlain by a marine and estuarine complex that covers a shelf rising gently inland to an old coastline lying at an elevation of about 23 feet.

At depth sands and gravels are widespread in the north west corner of the Fylde and have been interpreted as old beach deposits. Locally, east of the Wyre river, ridges of shingle rise through the clays and are thought to represent old storm beaches; the innermost extends south eastwards and very closely marks the inland limit of the alluvial complex.

Windblown sand is the most extensive of the more recent deposits in the study area. There are also contemporary marine and estuarine alluvium, especially on the saltings and near Fluke Hall as well as the contemporary storm beach, beach deposits, river alluvium and alluvial fans.

CHAPTER IV

HYDROGEOLOGY

Introduction

Water wells previously drilled in the Fylde area indicated low groundwater potential for the Bunter Sandstone aquifer. This work attempts to evaluate this potential more fully, to find more productive parts in the area and to ascertain the suitability of water for drinking purposes.

All water wells currently located in the map-area (including exploratory ones) are shown in Enclosure 4. Nearly all producing wells have been completed in the Bunter Sandstone formation, although a few, mainly in the west and northwestern sections of the area were completed in thin sand and gravel beds partially overlying the main sandstone aquifer.

Bunter Sandstone Aquifer System

Location and Extent

Bunter Sandstone aquifer is located in the centre of the Fylde, between the Carboniferous and Permian formations on the east, and the Keuper Marl on the west (Enclosure 1). This is the most important aquifer in the area and is completely represented only in the northern quarter of the area. It thins out in the centre and widens southwards to include Preston urban area.

Water Level and Groundwater Flow Characteristics in the Bunter Aquifer

The Bunter Sandstone has been increasingly developed as an aquifer over the past 20 years (Law, 1970). A relatively large quantity of data is available as a result of these activities. Static water levels in the Bunter Sandstone aquifer are presented as Enclosure 1. The data used for compiling this map were obtained from borehole records. The majority of wells in the area were drilled between 1950 and 1977, accordingly, the water level records have been collected over a long period of time. Thus it is appropriate to regard these results as approximate in view of the long period since the water levels were taken.

From the water level information, it is possible to suggest that groundwater in the Bunter aquifer is generally moving westward. Ineson (1970) points out that at best one can only draw inferences about groundwater flow in most of the aquifers in the Lancashire area. Inspection of the water level contours reveals considerable variability in the spacing. Such variability could occur because of differing rates of recharge to the aquifer or most likely because of differing permeabilities within the aquifer.

Recent investigations have suggested that the development of groundwater flow through the Bunter Sandstone broadly comprises both fissure and intergranular components (Crook, et al., 1973). The present investigation has pursued this conclusion quantitatively, with the aim of defining the

relative importance of these two components of flow in different areas.

Two possible mechanisms of groundwater flow within the Bunter Sandstone of the Fylde area have been suggested:

1. The horizontal intergranular permeability is relatively uniform with large variations in hydraulic conductivity being the result of different degrees of fissure development. This development was originally postulated by Brereton and Skinner (1974).
2. The horizontal intergranular permeability of the sandstone section shows pronounced lateral variations. The flow of groundwater in this case is enhanced by a variable and localized development of fissures. The importance of a localized fissure network in conveying water to a pumped well is governed largely by the intergranular permeability of the jointed sandstone in the locality. Only if the intergranular permeability is relatively high does the fissure development lead to a greatly increased borehole productivity. This postulate is largely consistent with the data presented by Crook, et al., (1973).

In order to find out which of these two postulates is more applicable to the Bunter Sandstone aquifer and assessing data by Worthington (1972) a comparison has been made of two frequency histograms of the specific capacity of six inch – diameter boreholes which partially penetrate the Bunter

Sandstone in places where the lower till succession comprises only clay (Figure 4). One histogram relates to boreholes where loosely consolidated sandstone was recorded and where a relatively high velocity of flow might be expected. The second relates to boreholes where hard compacted sandstone was recorded, sometimes with visible fissures, and where relatively weak horizontal component of intergranular flow is likely. There is a clear off-set in the two distributions, with that relating to loosely consolidated sandstones occupying the higher range.

These results indicate that it is intergranular permeability which controls variations in the production capacity of the aquifer and thereby constitute support for postulate No. 2. This means that the presence of fissure intersected by a pumped well should, in general, be more correctly regarded as irregular extensions of the borehole face at which intergranular flow terminates, rather than as regional features, which exercise a profound control over aquifer productivity.

Expected Yield of Groundwater from the Bunter Aquifer

Enclosure 5 shows groundwater probability in the study area. The values of transmissivity from earlier studies has been re-assessed and appear on a few wells on the map. Furthermore, a 20-year safe yield (amount of water which can be withdrawn for a 20-year period without producing undesirable effects), also calculated from the transmissivity values, is

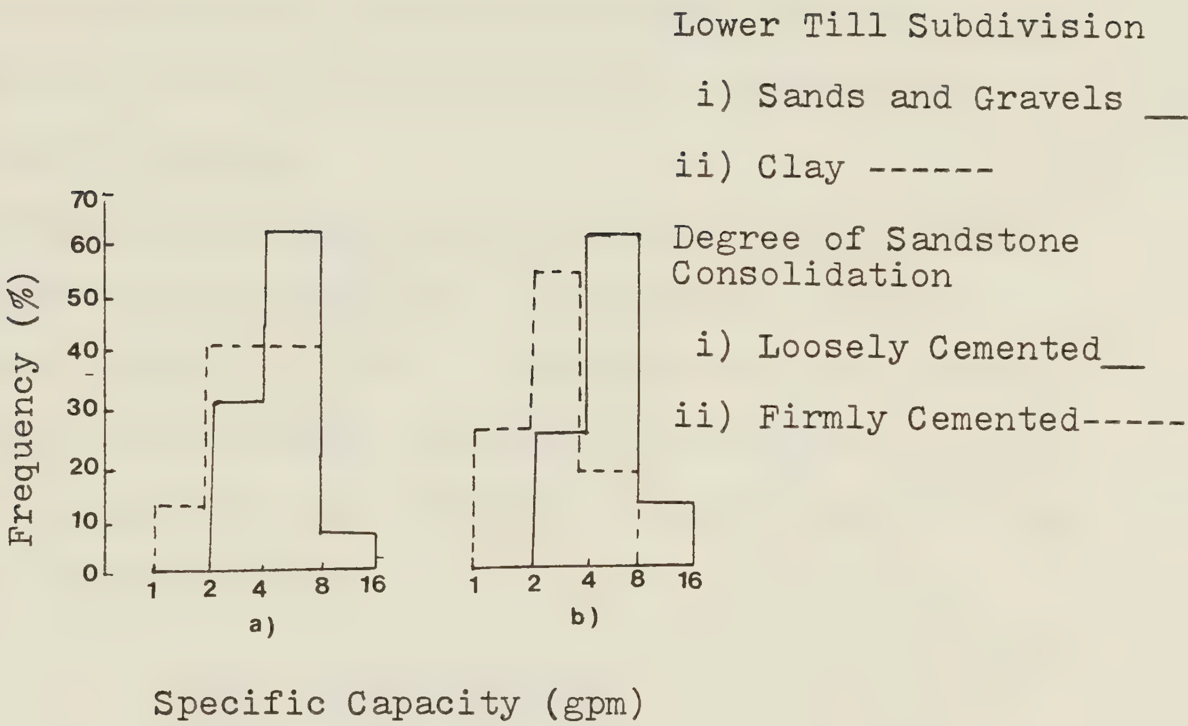


FIGURE 4

Comparison of histograms of specific capacity of 6 inch diameter boreholes in the Bunter Sandstone Aquifer

a) For different lower till lithologies

b) For different degrees of consolidation of the Sandstone

shown on the map.

Wells completed in soft red sandstone indicate that yields of over 75 igpm can be expected. Large areas with slightly less permeable deposits in the north and south can yield more than 25 igpm but less than 75 igpm. In the remaining parts of the study area excepting the eastern upland region adjacent to the Bowland county, yields of 10 to 25 igpm can be expected.

In all cases, the groundwater potential in the Bunter Sandstone aquifer is generally low. In order to ensure constant supply, discharge rates of more than 80 igpm, cannot be recommended, lower pumping rates would be necessary in certain areas, especially near barrier boundaries such as near St. Michael's bridge on Wyre.

Other Aquifer Systems

Apart from the Bunter Sandstone, which constitute the major aquifer system within the map-area, a few other aquifers of limited extent have been identified. These are:

1. Sand and gravel aquifer, and
2. Alluvial aquifers.

Sand and Gravel Aquifer

This aquifer is located in the upper centre part of the map-area and overlies the Bunter aquifer. The geometry of this aquifer is not well known; however, the mean saturated thickness of the aquifer is less than five feet. A few shallow wells have been drilled in these deposits and long-term

yields of up to 15 igpm have been obtained. By drilling deeper, however, the sandstone aquifer is tapped, hence most commercial wells are completed in the main Bunter aquifer.

Alluvial Aquifers

These aquifers occur along either sides of the Wyre river valley and extend only a few kilometers from the valley edge around St. Michael bridge on the Wyre. The general thickness of these aquifers is ten feet. Owing to the general thickness of these aquifers, they are volumetrically unimportant in the area, but locally they may be important as sources of potable water for shallow domestic wells. Several dug-out wells have been encountered, most of which yield low quantities of water.

The existence of other important aquifers within the area of investigation is highly unlikely. No springs of great importance have been found, either during the past or the present study. Small, seasonal springs were observed along the banks of the River Ribble and River Wyre.

Aquifer Testing Program

Introduction

A pumping test is one of the most useful means of determining hydraulic properties of water-bearing layers and confining beds. It may yield reliable results which, in general, are more representative of a large area than are single point observations.

During the course of the investigation, two pumping

tests were conducted; a step draw-down test for three hours and a constant rate test for three days. Three bail tests were also conducted in the north and southern sections of the aquifer. In each case the two-hour bail test was followed by a two-hour period of recovery.

Pumping Tests

On March 25th, 1977, Well No. SD44 SW/K (Appendices 1 and 3) was completed. A pump was installed at 130 feet depth and a step draw-down test was run. Three steps of one hour duration each were run at 20 gpm, 30 gpm and 45 gpm respectively.

Lennox (1966) and Sheahan (1971), discuss an analysis of step draw-down tests by which it may be determined whether turbulent flow conditions prevail in any of the steps. This was the main intention of conducting this test. In this technique Sw/Qn, or draw-down divided by pumping rate, is calculated at the end of each step. If the resultant values are approximately the same for all steps, laminar flow conditions prevail. The step draw-down data have been plotted on semilogarithmic paper and are presented in Figure 5.

In the present test, Sw/Qn increased with each step, thus indicating turbulent flow. The interpretation of these data to predict well loss (the increase in draw-down in a well over the normal draw-down due to formation loss) gave rather unreasonable values. However, Mogg (1968) demonstrates that step draw-down tests are not strictly reliable except inasmuch as the several steps may actually include or bracket the final pumping rate.

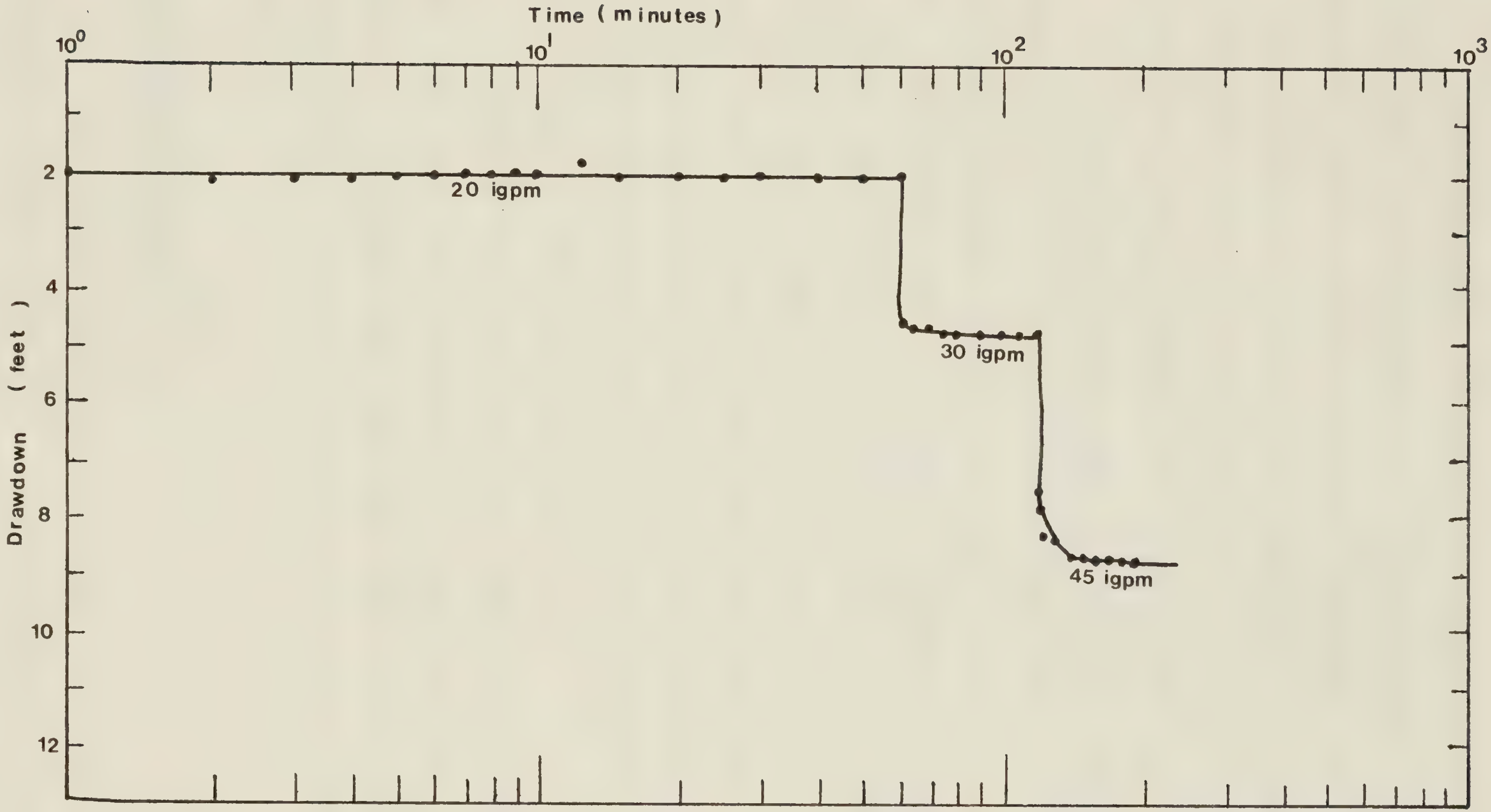


FIGURE 5

Step-drawdown Hydrograph, March, 1977. Pump Test, Well SD44 SW/k.

Furthermore, the pump was known later to have been installed by the driller within the slotted section of the aquifer. This possibly induced turbulent flow because most of the water being pumped was from the nine feet on the aquifer directly opposite the pump. Any change in the setting of the pump would considerably reduce the well loss.

About three miles east of the Well SD 44 SW/K, a pumping test was later conducted with Well SD 44 NE/T41a completed on April 19th, 1977, to a depth of 138 feet. The well was first blown out with a compressor, followed by constant pumping for three days at constant discharge rate of 60 igpm. An irrigation well 217 feet to the southwest and another well 95 feet to the north of the pumping well were used as observation wells, thus it was not necessary to drill new observation wells for the test. The construction of the wells and lithology are shown in Figure 6.

Before the pumping test began, the observation wells had been regularly monitored to establish the static water levels. Draw-down and recovery measurements were carried out using electric water level indicators Models DR-760 and MDP 122.

Analysis of Draw-down in Observation Wells

Draw-down data obtained from the observation wells were analyzed by the modified non-equilibrium formula developed by Jacob (1946), based on the theories by Theis (1935). This method is intended for the determination of transmissivity and

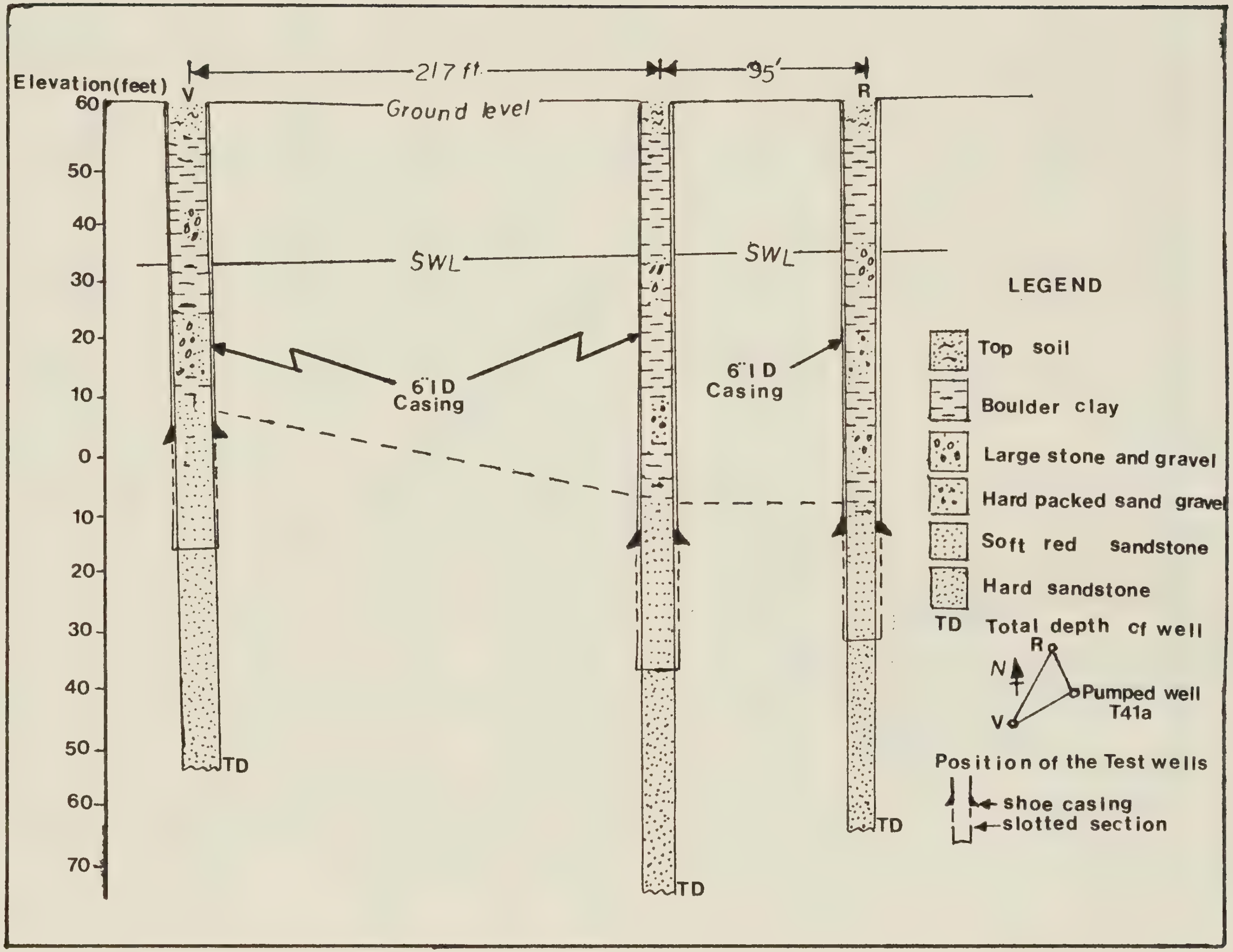


FIGURE 6

Logs of Test Holes 3 Day Pump Test (1977)

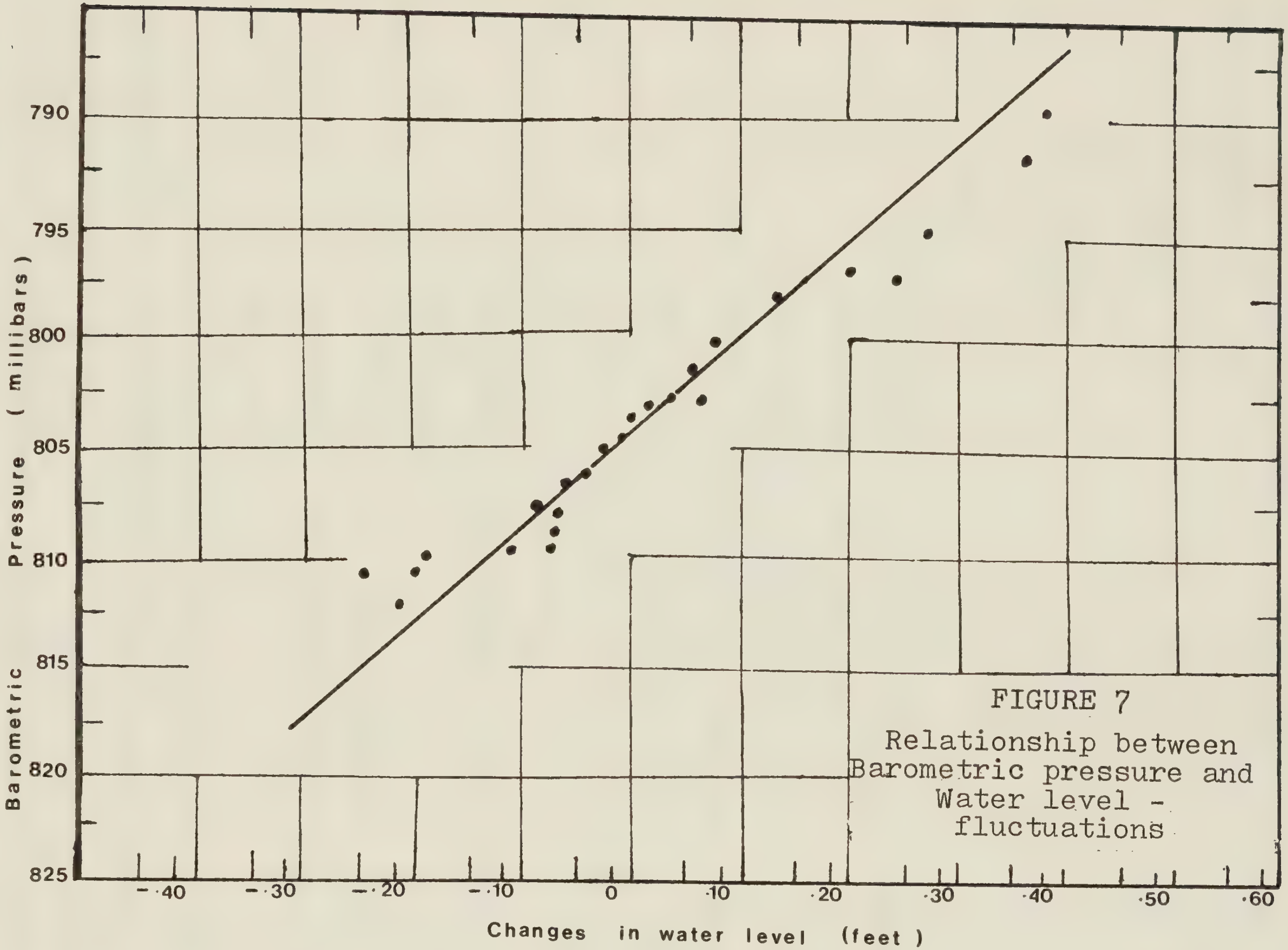


FIGURE 7

Relationship between Barometric pressure and Water level - fluctuations

storage coefficients in unsteady state flow in confined aquifers. The formulae used in the analysis of the data are given below:

$$T = \frac{264Q}{\Delta s}$$

$$S = \frac{0.36Tt_o}{r^2}$$

where

T = Coefficient of transmissivity in imperial gallons per day per foot;

Q = Discharge rate in imperial gallons per minute;

Δs = Slope of the time draw-down graph expressed as the change in draw-down between any two values of time on the log scale whose ratio is 10.

S = Coefficient of storage.

t_o = Intercept of the straight line at zero draw-down in days.

r = Distance in feet from pumped well to observation well where draw-down measurements were made.

The solutions for Jacob's method of analysis are shown in Figures 8 and 9. Transmissivity and Storage values obtained from the analysis are 8336 igpd/ft. and 6.3×10^{-5} respectively. for the first observation well, and 9900 igpd/ft. and 7.9×10^{-5} respectively for the second observation well.

According to Jacob (1946) the coefficient of storage can be reliably calculated by this method in the case of observation wells which are sufficiently distant from the

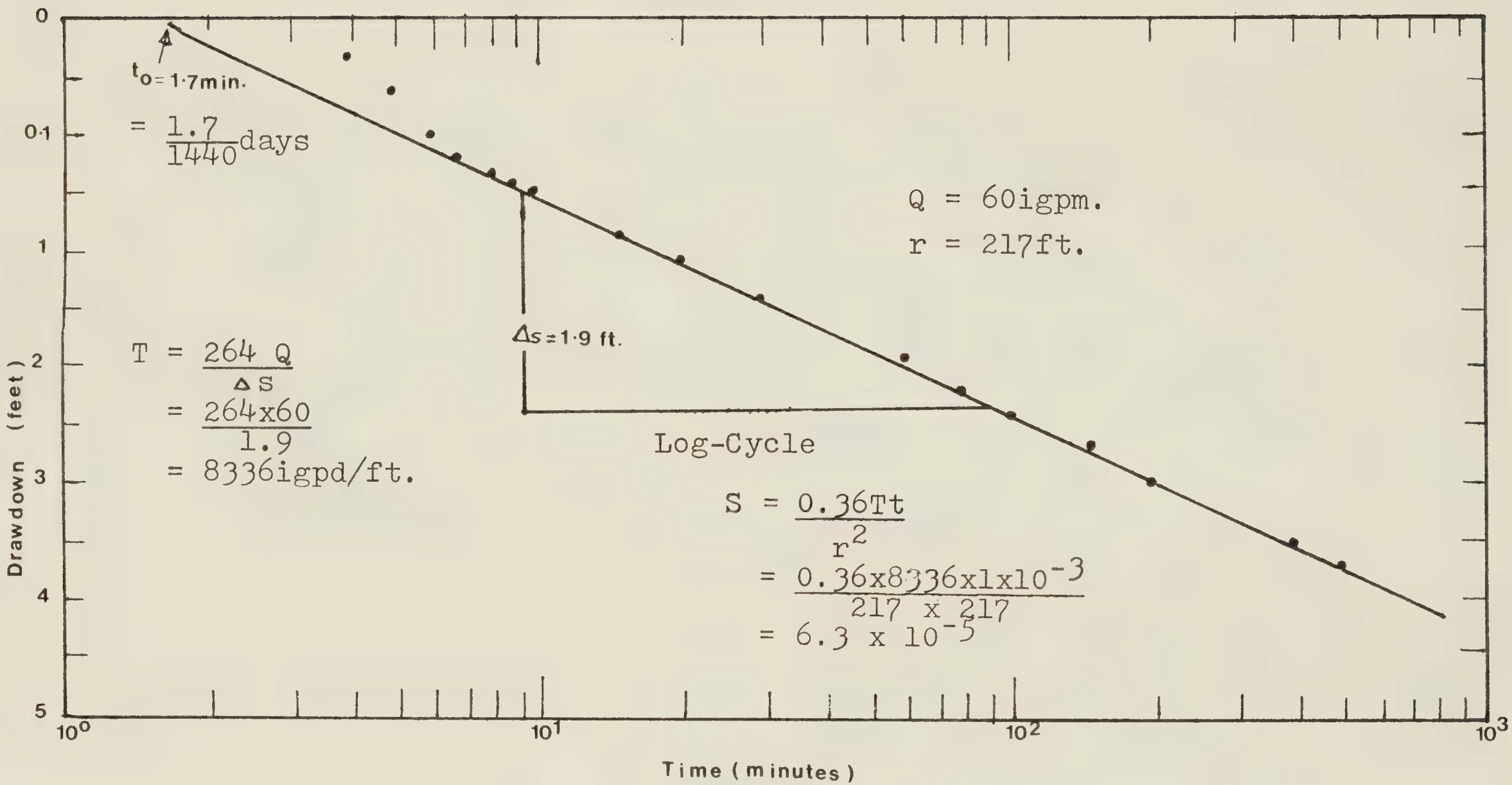


FIGURE 8

Time-drawdown graph, 1977 pump test, Observation Well No. 1 (Well V) 217 feet from pumping well SD44 SE/T41a. Jacob, 1946, Method of Solution.

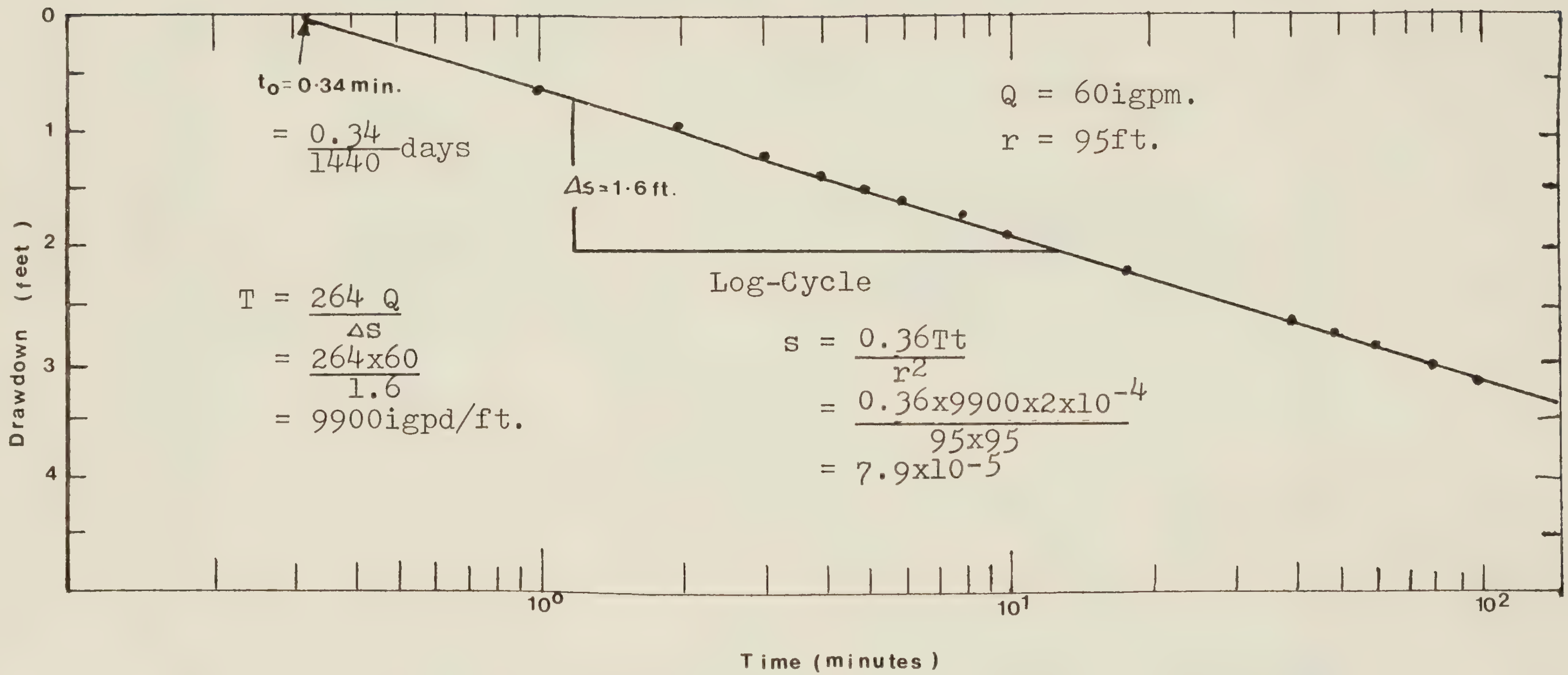


FIGURE 9

Time-drawdown graph, 1977 pump test, observation well No. 2 (Well R) 95 feet from pumping well. SD44 SE/T41a. Jacob, 1946, Method of Solution.

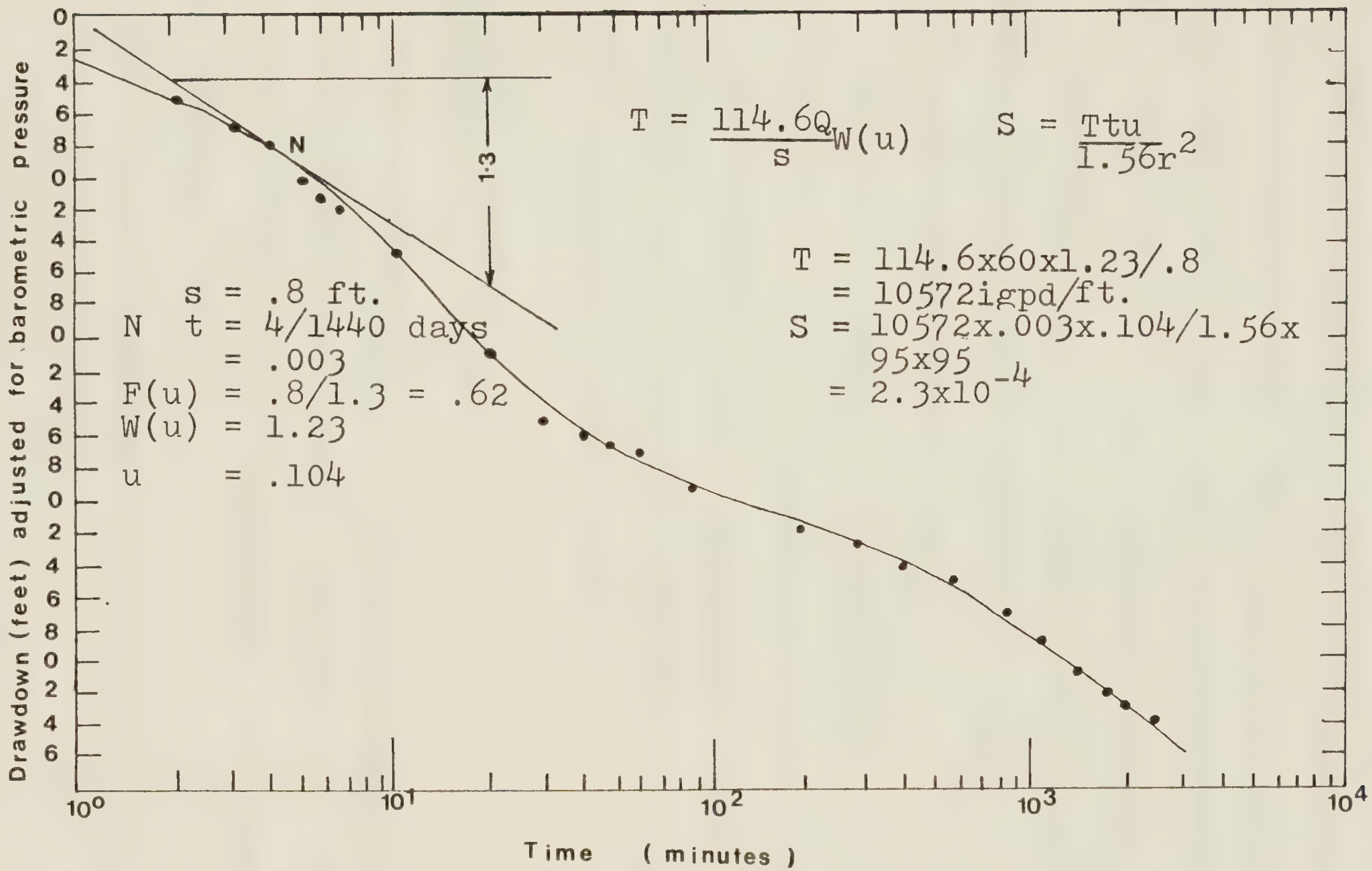


FIGURE 10

Time-drawdown Graph, April, 1977. Pumping Well SD44 SE/T41A. Chow, 1952, Method of Solution

pumping well. As the distances of 217 feet and 95 feet respectively were, in this case, considered sufficiently distant from the pumping well, the storage coefficient has been calculated, using this method.

The time draw-down curve for observation well No. 1, (Figure 8) located at 217 feet from the pumping well, deviates slightly from two to four minutes during the first ten minutes of the pumping period. This deviation affecting the earlier part of the curve, is likely to have been caused by insufficient correction of data from a drop in the non-pumping level or possibly by casing storage.

It can be observed that the values for transmissivity and storage obtained from the data at the two observation wells do not differ significantly. Deviations of the curve generally affect storage values but their influence on transmissivity values are negligible (Jacob, 1946).

Analysis of Draw-down in Pumping Well

Drawdown analysis in the pumping well was made by the graphical method of Chow (1952), (Figure 10). This method, which is a modification of Theis method of analysis, has three main advantages:

1. It enables the use of Chow monogram instead of Theis curve fittings.
2. It is not restricted to small distances between observation well and the pumping wells.
3. Small values of time can be used.

The formulae used in computing transmissivity and

storage coefficients by this method are:

$$T = \frac{114.6Q}{s} W(u)$$

and $$S = \frac{Ttu}{1.56r^2}$$

where T = Transmissivity in gallons per day per foot

S = Storage coefficient

t = Time since pumping begun, in minutes

W(u) = Well function.

Transmissivity and storage values obtained by this method were 10572 igpd/ft. and 2.3×10^{-4}, respectively. The analysis using this method are shown in Figure 10.

These results compare favourably with the values obtained in the two observation wells. The pumping test data showed no boundary effects. The only possible recharge boundary would have been the river Calder, one mile to the north of the pumping well.

Calculation of Safe Yield

The average value of apparent transmissivity obtained from the pumping test data and the bail test results, is 8100 igpd/ft. This value, according to the available information, cannot be readily associated with a particular formation. It can be pointed out, however, that the rate of draw-down after approximately one day of pumping at the location of the main pumping well fluctuated only slightly as if the formation of the storage of which water is withdrawn had a combination of the transmissivity value of 8100 igpd/ft. This value was therefore used in the calculation of safe yield.

The rate of draw-down stabilized at approximately 2500 minutes of pumping at 29 feet. (Appendix 3).

Tóth (1966) suggests that, in calculating the safe pumping rate at which the total available draw-down is used up by the end of the 20th year (approximately 10^7 minutes), the available draw-down can be calculated as the difference between the pre-test water level in the well and the top of the aquifer which in this case is 29 feet. A value for the 20-year safe yield can be achieved by rearranging the equation used in the calculation of transmissivity.

$$T = \frac{264\ Q}{\Delta s}$$

thus

$$Qs20 = \frac{T.H_{Avail}}{2110}$$

where

Qs20 = Safe yield supplied from existing storage for 20 years.

H_{avail} = Total available draw-down, taken as the difference between the non-pumping level and the top of the aquifer (Tóth, 1966).

Substituting T = 8100 igpd/ft. and H_{avail} = 29 feet, the safe yield is obtained.

$$Qs20 = \frac{8100 \times 29}{2110}$$

$$= 111 \text{ igpm (imperial gallons per minute).}$$

If we multiply this value by a safety factor of 0.71 (Tóth, 1966), we obtain approximately 79 igpm. It is

apparent, however, that at higher pumping rates than the one used here (60 igpm), a larger component of well loss would occur as this figure does not take this into account. The actual safe yield could be slightly smaller than 79 igpm, because this value does not take increases in well-losses into account.

Bail Tests Analyses

The bail tests formed one of the significant phases of the study program. The general procedures described by Tóth (1966a) were applied. The tests were conducted to a maximum of 20 imperial gallons per minute. Three bail tests were conducted, two in the northern part of the area and one in the south. A summary of the bail test results is shown in Table 2. The equation used in the calculation of the coefficient of transmissivity is (Todd, 1959, p. 94):

$$T = \frac{264\ Q}{\Delta s}$$

where

T = Coefficient of transmissivity in igpd/ft.,

Q = Discharge rate in igpm, and

Δs = Draw-down per log cycle.

The following summary of transmissivity (T) and safe yield (Qs20) for the study area is based on the results of testing conducted in the study. For the wells completed in Bunter Sandstone transmissivity determined from bail testing ranged from 880 igpd/ft., to 6600 igpd/ft. for the draw-down portion of the tests and from 1100 igpd/ft., to 9400 igpd/ft. for the recovery portion of the test. Calculated

TABLE 2

Bail Tests

Date	Location	Water-bearing formation	Head (H) at start of test (feet)	Type of test	Duration of test (minutes)	Q = Discharge rate (ippm)	Draw-down (s) in feet - Uncorr. for Bar. Pressure	Specific capacity = Q/s	Transmissivity igpd/ft. $T = \frac{264\ Q}{\Delta s}$	Qs20 (igpm) $Qs20 = \frac{TH}{2110}$
7/4/1977	NGR SD 487320	Bunter Sandstone	24	Bail (bailing)	120	20	0.8	25	6600	75
				Bail (recovery)	120				9400	106
8/4/1977	NGR SD 496445	Bunter Sandstone	53	Bail (bailing)	120	20	6	3.3	880	22
				Bail (recovery)	120				1100	28
12/4/1977	NGR SD 494422	Thin gravel (Inter-mediate)	76	Bail (bailing)	120	16	11	1.5	384	14
				Bail (recovery)	120				-	-

20-year safe yields ranged from 22 igpm to 106 igpm. For the wells completed in thin sections of gravels, sands and other materials, transmissivity diminishes to 385 igpd/ft. and Qs20 = 14 igpm. Obviously the values for the well in drift cannot be representative of the groundwater potential in the study area because the well did not tap more productive zones of the sandstone aquifer.

Considering the general hydraulic characteristics of most sandstone aquifers, the values obtained for T and Qs20 can serve as a useful guide. However, they are not representative of the conditions in the entire Bunter Sandstone aquifer. Although bail tests have been found to be generally reliable, two inherent inaccuracies that result from the use of the method are important:

1. Inaccuracy in their absolute values, which is due to the fact that the mathematical formulae used in the calculation of T are strictly valid only for idealized geologic conditions which do not usually exist in nature.
2. An inherent inaccuracy resulting from the fact that bail tests are normally conducted for too short a period to allow for the appearance of barrier boundaries which would otherwise have an effect on the results.

CHAPTER V

GROUNDWATER CHEMISTRY

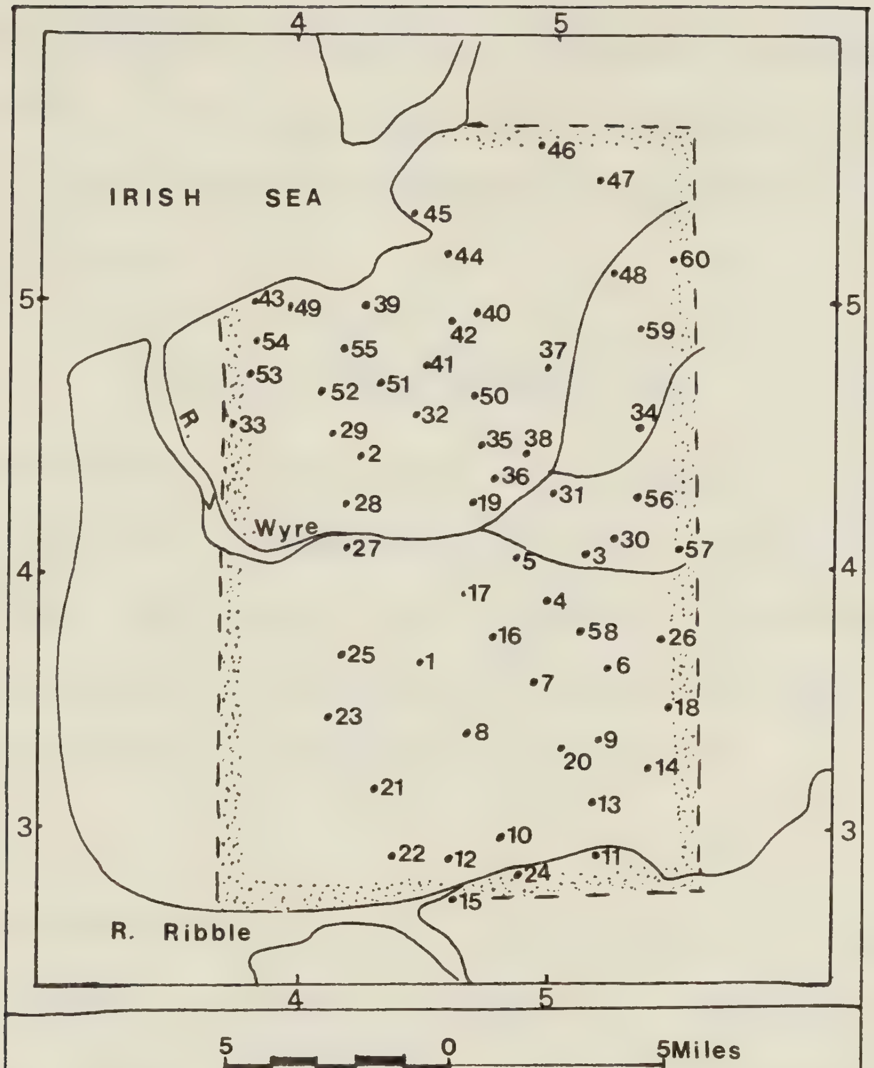
Introduction

During the course of the investigation, 60 groundwater samples were collected and analyzed. The data were obtained during Autumn, 1976 and Spring, 1977. The complete analyses of these samples are presented in Appendix 2. Locations of the sampling sites are shown in Figure 11. Samples were analyzed for the following ions: Sodium (Na^{+}), Potassium (K^{+}), Calcium (Ca^{++}), Magnesium (Mg^{++}), Chloride (Cl^{-}), Bicarbonate (HCO_3^{-}), Carbonate (CO_3^{--}), Sulphate (SO_4^{--}), Nitrate (NO_3^{-}), and Iron (Fe^{++}). Total dissolved solids, temperature, pH and specific conductance were also determined.

The purpose for the investigation of groundwater chemistry in the Fylde area was twofold:

1. To obtain detailed information regarding suitability of the groundwater in the area for human consumption.
2. To relate groundwater chemistry to local geology, groundwater movement and the presence of the sea nearby.

In the study area, water from the sandstone aquifer is generally of good quality with low dissolved constituents,



.42 Numeral denotes
sample number

Ground Water Sampling Sites
The Fylde, Lancashire - 1976/77
Boundary of Study Area

FIGURE 11

Groundwater Sampling Sites

but water obtained from marl, till, silt, clay or more permeable lenses within these materials tends to be of poorer quality.

The recommended limits of chemical constituents in drinking water in Britain, are shown in Appendix 4. The recommended limits for livestock and irrigation in England are slightly higher.

Distribution of Major Ions

The cations present in the groundwater of the study area are, in order of abundance: calcium, sodium, magnesium and potassium. The anions are bicarbonate, sulfate, chloride, nitrate and carbonate. These major ions will be treated separately in the following sections.

Cations

The distribution of the major cations in the Bunter Sandstone aquifer is shown in Figure 12. Calcium, which is the dominant cation is generally uniformly distributed with the highest concentration (300 ppm) in the northwest part of the area.

Hem (1959) and Davis and De Wiest (1966) state that subsurface waters in contact with sedimentary rocks of marine origin derive most of their calcium from solution of calcite, aragonite, dolomite, anhydrite and gypsum. This also appears to be the source of calcium in the study area although aragonite and dolomites are not well developed. Water in the Bunter Sandstone is characterized by low

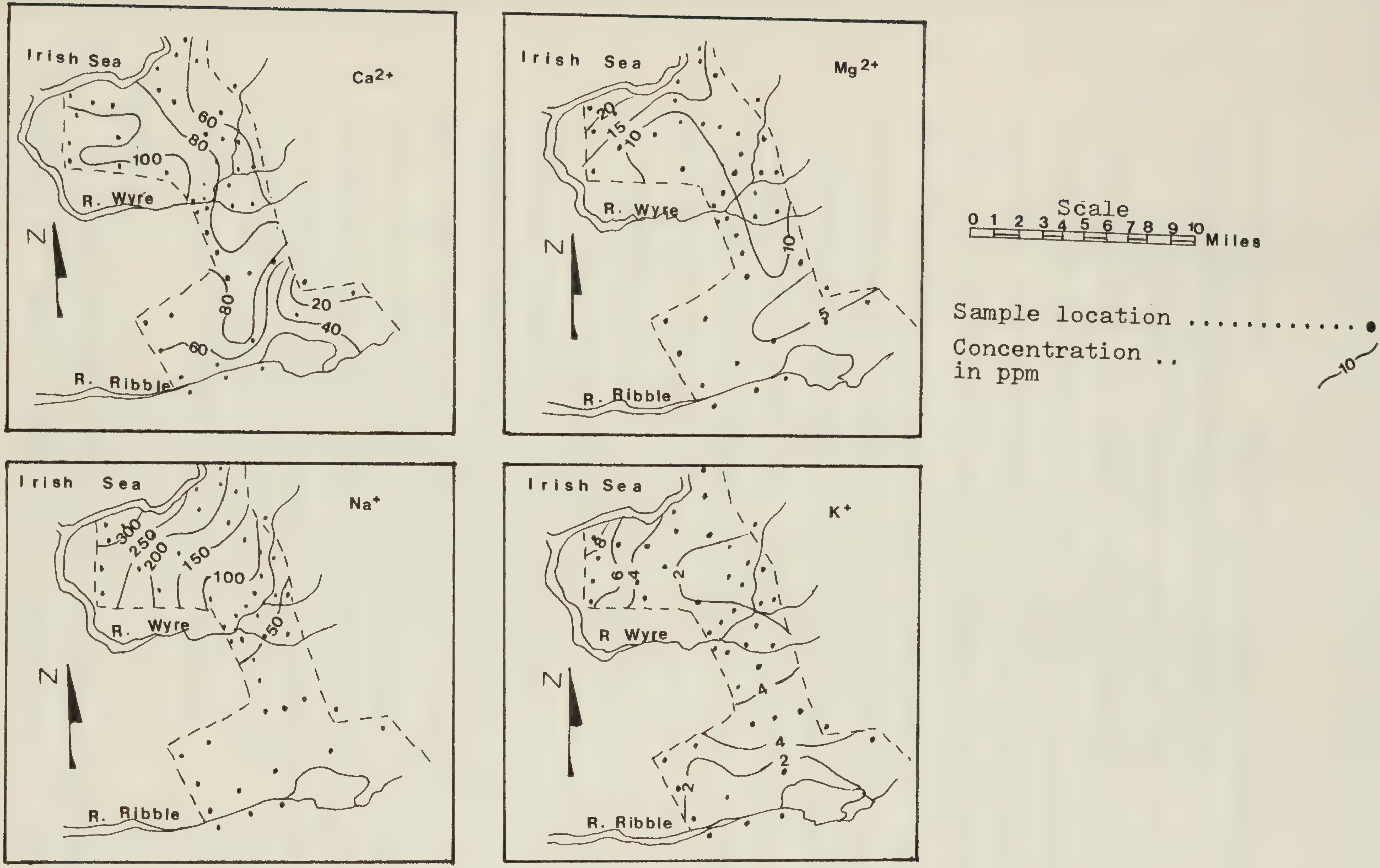


FIGURE 12

Distribution of Major Cations in the Bunter Sandstone

magnesium content. About 80 per cent of the samples analyzed show magnesium concentration of under 20 ppm.

Chebotarev (1955) points out that the calcium: magnesium ratio in natural waters is generally believed to change only slightly along short paths of groundwater movement. It has also been noticed (Hem, 1959) that most waters are of low to moderate dissolved-solids concentration, magnesium content is considerably less than calcium, even when computed on the basis of concentrations expressed in equivalents per million. A similar situation has been observed in the study area. However, the calcium:magnesium ratio increases or decreases noticeably at the discharge areas in the western portion of the area; while the changes are remarkably slight in the recharge area.

Other cations determined included sodium and potassium. These two ions, in most cases, have not been determined separately. It can be seen from Figure 12, that high concentrations of both Na^+ and K^+ predominate in the north and northwest of the Bunter Sandstone. The low concentrations of Na^+ (less than 50 ppm) have been mapped in the southern half of the sandstone. The water in this part of the aquifer was obtained from shallow wells. The two areas vary topographically and geologically.

Anions

The relative distribution of major anions together with pH are shown in Figure 13. Bicarbonate is by far predominant, constituting more than 60 per cent of the total

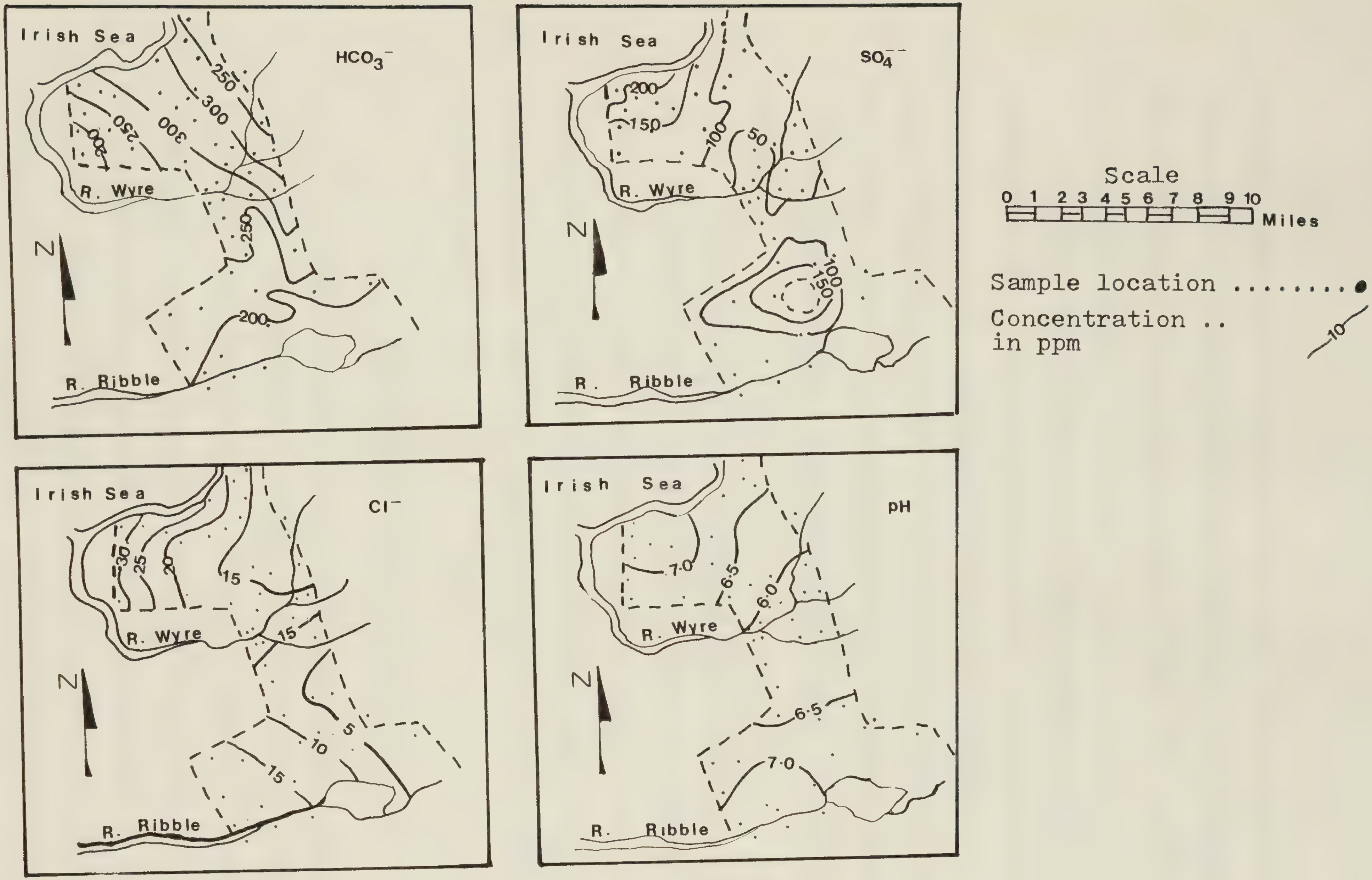


FIGURE 13

Distribution of Major Anions in the Bunter Sandstone

anions. Here, the same general pattern is obtained as was presented on the map of the major cations. The highest HCO_3^- concentrations were measured in the north central part of the study area.

Apart from bicarbonate, chloride and sulfate constitute the remaining major anions. Chloride, although commonly a minor constituent of the earth crust, is a major dissolved constituent of most natural water. Within the Bunter aquifer, the distribution of chloride varies from 5 ppm in the south and east to over 30 ppm in the north and west.

The values of PH determined from various sections of the map-area are shown in Figure 13. The PH values range from 6.4 to 7.2 and are relatively uniformly distributed. Generally, PH increases from the south to the north of the Bunter aquifer, with the highest value (7.2) attained just west of Garstang.

Origin of Chemical Patterns

In the northern half of the study area, comparison of the anion distributions (Figure 12) and the groundwater flow directions inferred from Enclosure 1, suggest a gradual increase in concentrations along the flow system. A similar but less consistent pattern exists with respect to the major anions - particularly SO_4^{2-} and Cl^- (Figure 13). These well defined geochemical patterns can probably best be explained in terms of several possible mechanisms. Mineral dissolution or megascopic dispersion (large scale mixing) are the most

plausible alternatives.

By analogy, with systems elsewhere in the world, a mineral dissolution model might be explained as follows. Recharge waters passing through a soil zone would rapidly acquire Ca^{2+}, Mg^{2+} and HCO_3^- ions primarily from the rapid dissolution of carbonate rocks. Concentrations of these and other species such as SO_4^{2-}, Cl^- and Na^+ would slowly increase with the dissolution of small quantities of soluble salts. The calcite and possibly dolomite equilibria would ultimately control the concentration of Ca^{2+} and Mg^{2+} in solution. Unfortunately, there are no mineralogical data available to corroborate a mineral dissolution model.

A megascopic dispersion model would act to produce the observed chemical pattern simply by mixing. Waters moving along the Bunter Sandstone from recharge areas in the northwest could be progressively mixing with more saline formation waters entering the aquifer from deeper units. Such a situation could give rise to the observed patterns. Swenson (1968) has proposed a somewhat similar pattern to explain anomalous chemical patterns in the Dakota Sandstone in the United States; although there are not sufficient data available to support adequately, prove or disprove this hypothesis, it is an attractive one because it could explain the evolution of the ion assemblage as a whole. It is clear that additional studies will be required to clearly explain the chemical patterns in this part of the study area.

The same possible processes could give rise to the

chemical patterns observed in the southern half of the study area. However, I have decided to deal with this area separately because of the significant differences in the chemistry. Generally, concentrations of Mg^{2+}, Na^{+}, HCO_3^{-}, SO_4^{2-} and Cl^{-} ions are less than in the northern half of the study area (Figures 12 and 13) and the variations less well defined. In the case of SO_4^{2-}, there is a marked high concentration zone present.

Using the dissolution model, one could argue that the lower concentrations stem from simply a reduced concentration of soluble salts in this portion of the aquifer. Using the dispersion model, one could argue that an increased transmissivity in this part of the aquifer would result in an overall reduction in the proportion of the water contributed from deeper units. Inspection of the transmissivity map of the aquifer (Enclosure 5) would appear to justify the dispersion model.

With the present data, the origin of the high SO_4^{2-} ion concentration remains an unsolved problem.

The Influence of the Irish Sea

The existence of the Irish Sea to the west of the study area has had an effect on the chemical pattern of groundwater in the area. A remarkable increase in the amount of dissolved solids in the groundwater in the alluvium towards the sea has been observed in the northwestern part of the Bunter aquifer. In that area, salinity concentration of groundwater increases from 2,000 ppm at Preesal to over

TABLE 3

Average Chemistry of Rainfall and Groundwater[1]

		Ionic Concentration (ppm)							
Type	No. of Samples	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^-	Cl^-	pH
Rainfall	5	6	1.1	3.0	0.4	4.2	9.1	3.2	6.0
Groundwater	60	86.3	11.6	44	40	278	28.9	28.9	6.8

Source: - Scientific Research Department,
British Meteorological Office (1976)

[1]Sample No. 43 rejected because values uncharacteristically too high.

13,000 ppm near Fleetwood.

Normally the increase in salinity concentration in groundwater towards the sea is due to its enrichment by soluble matter in the zone chloride-sulphate accumulation (Chebotarev, 1955). The occurrence of salt water due to sea-water intrusion has been recorded in several boreholes east of Fleetwood, where the water-bearing sandstone formation is apparently open to sea-water. Water samples taken from boreholes in the area indicate high concentrations of sodium and chloride (e.g. sample nos. 11, 43 and 53, Appendix 2).

The sea-water intrusion in the northwestern section of the Bunter aquifer constitutes a major threat to the groundwater quality. Before intensive studies can be carried out, groundwater exploitation in the area must be controlled. A pumping borehole near the coast will tend to increase the length of the salt-water wedge, and excessive pumping of a fresh-water well in the area is likely to result in contamination with salt-water. Unfortunately, the rate at which the situation can be reversed is much slower than the contamination process, and thus it is important to control abstraction near the coastline.

Suitability of Water for Consumption

Water consumption in the Fylde area can be roughly divided into two classes - domestic and agricultural. Hardness, iron and maganese, fluoride, sulfate, chloride, and nitrate contents are of primary concern to the domestic

consumer. The total mineral content, the ratio of sodium to calcium and magnesium, the carbonate, and the boron content largely determine the suitability of water for irrigation.

Chemical analyses of groundwater samples collected in the study area are given in Appendix 2, and the concentrations of Fe^{2+}, NO_3^- and TDS in the Bunter Sandstone aquifer are shown in Figure 14. The dissolved mineral contents in the area of investigation range from 200 to 1,000 micromhos. This conductance range is approximately equivalent to 100 to 800 ppm of dissolved solids which is low when compared to other potable groundwaters in northern England (Ineson, 1968). As discussed previously, the increase of the total dissolved-solids content in the Bunter aquifer from east to west (Figure 14) is attributed to progressive mineral dissolution or large scale dispersive mixing, although the total dissolved solids concentration in the extreme northwestern section of the Bunter aquifer may range from 1,000 to 9,000 ppm. The mean concentration for the remainder of the aquifer is approximately 400 ppm, thus the water meets drinking water standards with respect to salinity.

A similar pattern to the one described above has been observed in the distribution of iron concentration within the Bunter aquifer. Most of the water samples analyzed (Appendix 2) report iron concentrations of less than 1 ppm. Fifteen of the water samples, however, show iron content of more than 1 ppm. Such localized zones of high

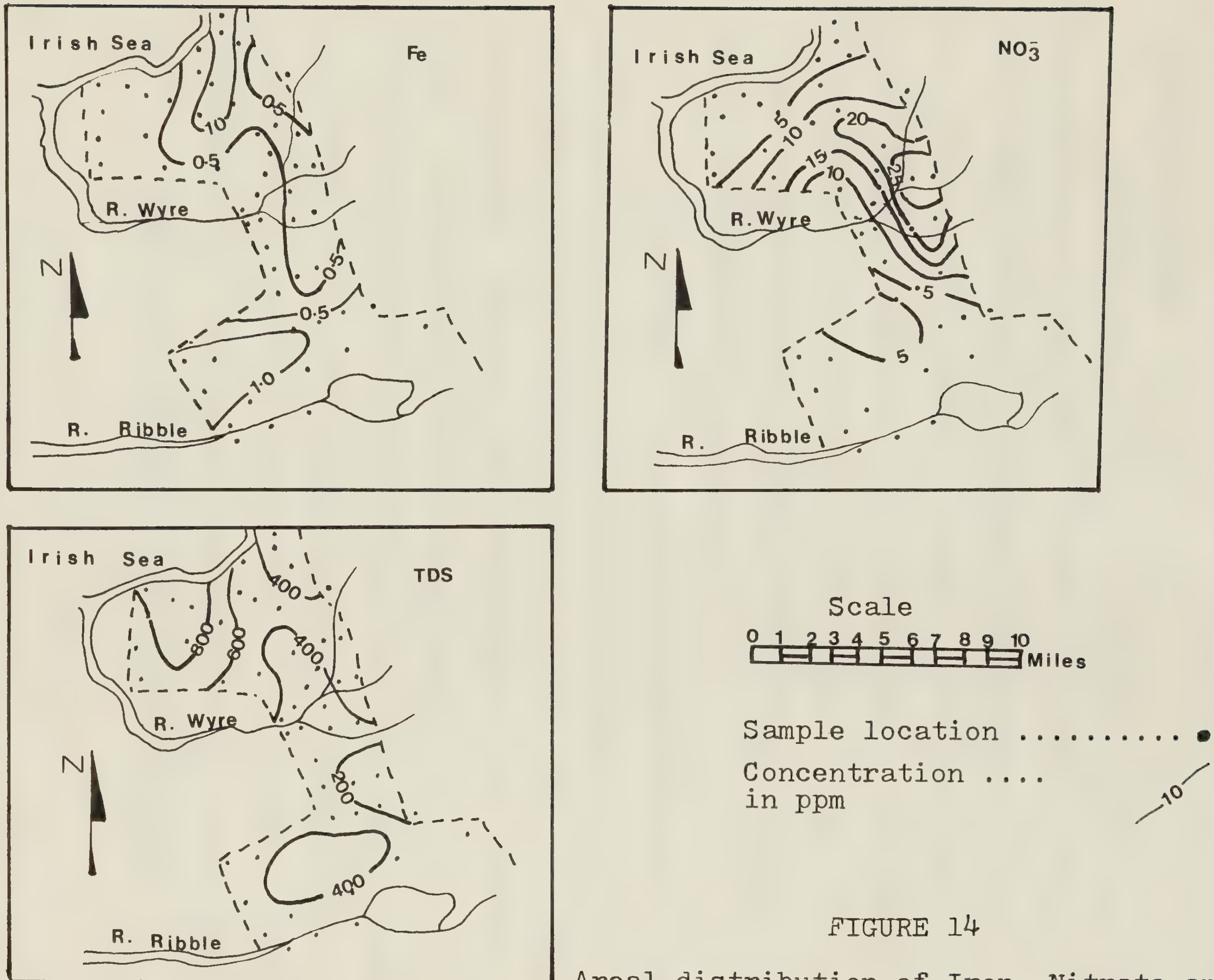


FIGURE 14

Areal distribution of Iron, Nitrate and Total Dissolved Solids in Bunter Sandstone

iron content are clearly unfavourable in water intended for drinking purposes.

Besides TDS and Fe^{2+}, the distribution of NO_3^- in the groundwaters of the Fylde is worthy of special attention. The pattern observed for nitrate is a reverse of the situation in Fe^{2+} and TDS. Within the map-area NO_3^- ion concentration ranges between 0 and 176 ppm. Most samples, however, show concentrations of less than 40 ppm. However, in the eastern section of the aquifer, concentrations of more than 70 ppm have been recorded.

A comparison of the systematic distribution of the major ions, the total solids and pH (Figures 12, 13 and 14) indicates that groundwater in most parts of the main Bunter aquifer meets standards for domestic use. The concentrations of Fe^{2+}, however, is considerably greater than the recommended standards, and measures must be taken to reduce ion content in the water intended for drinking purposes. Furthermore, high NO_3^- concentration in the water in addition to producing certain health problems may be indicative of waters seriously contaminated with other compounds.

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

A comparatively detailed evaluation of groundwater potential was completed over an area of approximately 120 square miles in the Fylde area of Lancashire. The most important regional aquifer is the Bunter Sandstone which underlies an area of approximately 75 square miles. This sandstone aquifer ranges in thickness from 50 feet to 600 feet. It is mainly confined although in certain sections, unconfined conditions prevail.

This study has contributed to a better understanding of the geology, hydrology, hydrochemistry and the potentiality of groundwater in the area, resulting in a number of conclusions that are of both local and regional significance. They are as follows:

Hydrologic Conclusions

i) Three aquifers were defined and described by the study: Bunter Sandstone aquifer; sands and gravel aquifer; and alluvial aquifers.

ii) The Bunter Sandstone aquifer is sufficiently transmissive and extensive to develop moderate yield (80-200 gpm) wells. The sand and gravel aquifer, and the alluvial aquifers have limited saturated thicknesses (less than 20 feet) hence are volumetrically unimportant in the area.

iii) Variation in the production capacity of the Bunter aquifer appears to be controlled by intergranular permeability and fracture modification.

Hydrochemical Conclusions

i) A well defined pattern in cation and anion distributions is evident for the Bunter Sandstone. The patterns are particularly well defined in the northern half of the study area and indicate an increase in nearly all major cations and anions in the direction of flow. In the southern part of the area, ion concentrations are lower and the variation in ion concentrations is less regular.

ii) Either of two mechanisms - mineral dissolution or megascopic dispersion may probably be responsible for generating these patterns. The mineral dissolution model would propose that the general concentration increases along the direction of flow are the result of continued dissolution of a variety of mineral phases. The megascopic dispersion model would involve mixing of deeper and more saline formation waters with fresher waters flowing in the aquifer. The net result in this case would be a gradual increase in cation and anion concentrations. Unfortunately, data are not sufficient to identify the process more correctly.

iii) Several constituents - nitrate and ferrous iron -

are present at concentrations which could diminish the quality of water for certain domestic uses. It is suggested that locally high nitrate concentrations may be related to excessive use of nitrate fertilizers. The locations where iron concentrations are one part per million, are the extreme north and southwest portion of the Bunter Sandstone. Concentration at this level are typical for natural groundwaters. With the exception to localized problem wells, water in the Bunter Sandstone meets British health standards.

iv) Evidence exists of a possible threat to groundwater quality in the northwest section of the aquifer caused by sea water intrusion. Accordingly, production of groundwater in the coastal areas must be carefully monitored with more detailed evaluations of the seriousness of the problem.

BIBLIOGRAPHY

BIBLIOGRAPHY

BOULTON, N.S. 1954a. The drawdown of the water table under non-steady conditions near a pumped well in an unconfined formation: London, Proc. Inst. Civil Engineers, pp. 564-579.

________. 1963. Analysis of data from non-equilibrium pumping tests allowing for delayed yield from storage: London, Inst. Civil Engineers Proc., v. 26, pp. 469-482.

BRERETON, N.R. and SKINNER, A.C. 1974. Groundwater flow characteristics in the Triassic sandstone in the Fylde, Lancashire. Water Serv., 78, pp. 275-279.

BROWN, R.H. Konoplyantsev, A.A., Ineson, J. Kovalevsky vs. Ed., 1969, Ground Water Studies. An International Guide for Research and Practice UNESCO.

CHEBOTAREV, I.I. 1955. Metamorphism of natural waters in the crust of weathering. Geochemica et Cosmochimica Acta, v. 8, parts 1-3. 75 pages.

CHOW, V.T. 1952. On the Determination of Transmissibility and Storage Coefficients from Pumping Test Data. Trans. Amer. Geophy. Union, Vol. 33, No. 3.

COOPER, H.H. Jr., and JACOB, C.E. 1946. A generalized Graphical Method for evaluating Formation Constants and Summarizing Well-field history. Trans. Am. Geophy. Union. Vol. 27.

CROOK, J.M. 1970b. The Characteristics and Structure of the Permotriassic Sandstone aquifer of the Liverpool and Manchester industrial region of north-west England. Int. Symp. Groundwater, Palermo, December, 1970, pp. 217-25.

________, WOODHEAD, F.A., and WORTHINGTON, P.F. 1973. Permeation properties of Bunter Sandstones from Cheshire and Fylde Basins. Geotechnique, 23, pp. 262-65.

DAVIS, S.N., and DE WIEST, R.J.M. 1966. Hydrogeology; John Wiley and Sons Inc., 463 pages.

DAW, G.P., HOWELL, F.T., and WOODHEAD, F.A. 1974. The effect of applied stress upon the permeability of some Permian and Triassic sandstones of Northern England. In: Advances in Rock Mechanics, National Academy of

Sciences, Washington, D.C., pp. 537-542.

DOMINICO, P.A. 1972. Concepts and Models in groundwater hydrology. McGraw Hill Book Co., New York, p. 406.

DUROV, S.A. 1948. Classification of Natural Waters and Graphic Representation of their Composition: Doklady Akad. Nauk SSSR, 59, No. 1, pp. 87-90.

EASTWOOD, T. 1953. Northern England, British Regional Geology. Her Majesty's Stationary Office, London.

EDWARDS, W. and TROTTER, F.M. 1954. British Regional Geology - The Pennines and Adjacent Areas, 3rd Ed. Her Majesty's Stationary Office, London.

FOLK, R.L. 1959. Petrology of Sedimentary Rocks. Austin, Hemphilis, Texas, p. 154.

FOSTER, M.D. 1950. The origin of high sodium bicarbonate waters in the Atlantic and Gulf Coast Plain: Geochim et Cosmochim Acta, V. 1, pp. 33-48.

FREEZE, R.A. and WITHERSPOON, P.A. 1966. Theoretical Analysis of Regional Groundwater Flow: 1. Analytical and Numerical Solutions to the Mathematical Model; Water Resources Research, Vol. 2, No. 4, pp. 641-656. 2. (1967). Effects of water table configuration and subsurface permeability variations. Water Res. Vol. 3, pp. 623-634.

GORHAM, E. 1955. On the acidity and salinity of rain: Geochim et cosmochim Acta, v. 7, pp. 231-239.

HEM, J.D. 1970. Study and Interpretation of the Chemical Characteristics of Natural Waters; U.S. Geol. Survey Water Supply paper 1473; 361 pages.

HUBBERT, M.K. 1940. The theory of groundwater motion; Journ. Geol. Vol. 48(8), Part 1, pp. 785-944.

INESON, J. 1970. Development of Groundwater Resources in England and Wales. Jour. I.N.E. Vol. 24, p. 245.

JACOB, C.E. 1940. On the flow of water in an elastic Artesian Aquifer Trans. Amer. Geophy. Union, pt. 2, pp. 574-586.

________. 1945. Partial penetration of pumping well, adjustments for; U.S. Geol. Surv. Water Resources Bull., August.

________. 1946. Drawdown Test to determine effective radius of Artesian Well. Proc. Amer. Soc. Civ. Eng. Vol. 72, No. 5, pp. 620-646.

JOHNSON, E.E. 1966. Groundwater and Wells. E.E. Johnson, Inc., St. Paul, Minn., p. 440.

KING, H. 1967. Essays in Regional Geography of Great Britain. Orgilve, Cambridge Univ. Press, 502 pages.

KOLBUSZEWSKI, J. and SHOJOBI, J.O. 1965. Chemical Analysis of Keuper Marl. The Surveyor, Great Britain, No. 3799.

KRUMBEIN, W.C. and PETTIJOHN, F.J. 1938. Manual of Sedimentary Petrology, Appleton Century Crofts, Inc., New York.

KRUSEMAN, G.P. and De RIDDER, N.A. 1970. Analysis and Evaluation of Pumping Test Data. Int. Inst. for Land Reclamation, The Netherlands Bull. 11, p. 200.

LANE, E.W. and others. (1947). Report of the Subcommittee on Sediment Terminology: Am. Geophy. Union Trans., V. 28, No. 6, pp. 936-938.

LAW, F. 1970. Notes for talk regarding conjunctive use of water resources by the Fylde Water Board.

LENNOX, D.H. 1966. Analysis and Application of Step Draw-down Test. Proc. Am. Soc. Civ. Engineers, HY6.

MEINZER, O.E. 1923. Outline of Groundwater Hydrology. U.S. Geol. Survey Water Supply Paper 494. 71 pages.

MEYBOOM, P., VAN EVERDINGEN, R.O. and FREEZE, R.A. 1966. Patterns of Groundwater flow in seven discharge areas in Saskatchewan and Manitoba. Geol. Surv. of Canada. Bull. 147, 57 pages.

MOGG, J. 1959. The effects of Aquifer Turbulence on Well Draw-down. Proc. Am. Soc. Civil Eng. Hydr. Division. November, pp. 99-112.

________. 1968. "Step-drawdown test needs critical review": Johnson Drillers Journal, July-August, 1968, pp. 3-11.

MORLEY, L.W. 1967. Mining and Groundwater Geophysics, Economic Geology Report No. 26. Geological Survey of Canada, 722 pages.

MUSKAT, M. 1937. The flow of homogeneous fluid through porous media; McGraw-Hill Book Co. Inc., New York, p. 763.

RENICK, B.C. 1925. Base exchange in groundwater by silicates as illustrated in Montana, U.S. Geol. Survey Water Supply paper. J20-D, pp. 53-72.

SWENSON, F.A. 1968. New theory of recharge to the Artesian basin of the Dakotas. Bull. Geol. Soc. Amer., Vol. 79, pp. 163-182.

SEABER, P.R. 1965. Variations in chemical character of water in the English town formation, New Jersey, U.S. Geol. Surv., Prof. paper 498-B.

THEIS, C.V. 1935. The relation between the lowering of Piezometric surface and the rate and duration of discharge of a well using groundwater storage, Am. Geophy. Union Trans., Vol. 16, pp. 519-524,

TODD, D.K. 1959. Groundwater Hydrology. John Wiley Inc., New York, 336 pages.

TÓTH, J. 1962. A theory of groundwater motion in small drainage basins; Journ. Geophy. Res. Vol. 67, No. 11, pp. 4375-4387.

________. 1963. A theoretical analysis of groundwater flow in small drainage basins; Journ. Geophy. Res. Vol. 68, No. 16, pp. 4795-4812.

________. 1966a. Groundwater geology, movement chemistry and resources near Olds, Alberta; Res. Council Alberta, Bull. 17, 126 pages.

VEREISKII, N.G. and VASTOKOVA, E.A. 1963. Guide book for determining the Lithological composition of surface deposits and depth of occurrence of groundwaters. Translated from Russian by Israel Prog. for Sci. Translation, Jerusalem, 246 pages.

WALTON, W.C. 1962. Selected analytical methods for well and aquifer evaluation; Illinois State Water Survey, Bull. 49, 81 pages.

________. 1970. Groundwater Resources Evaluation. McGraw-Hill Book Co., New York, 660 pages.

WORTHINGTON, P.F. and BARKER, R.D. 1972a. Methods for the calculation of true formation factors in the Bunter Sandstone of north-west England. Eng. Geol. 6, pp. 213-28.

________. and GRIFFITH, D.H. 1975. Application of Geophysical methods in the exploration and development of sandstone aquifers. Q. Jl. Eng. Geol., Vol. 8, pp. 73-102.

WRIGHT, J. 1952. The British Code of Stratigraphy. Institute of Geol. Survey, 2nd edition, p. 97.

APPENDICES

APPENDIX 1

Description of Borehole Sections and Samples

The purpose of this Appendix is to present the basic geologic data (lithologic description of representative borehole sections and samples) upon which this study was based.

The description has been possible largely due to the high quality of samples obtained during this and previous investigations. The samples were obtained by rotary drilling methods. I have also included a few drillers' logs which I have re-examined in the area. A large number of samples from some of the wells drilled in the past were saved and have been examined. Consequently, the samples saved and the drillers' original field descriptions which are on file, have been thoroughly correlated.

The classification system of the terrigenous rocks and grain size terminology follows the recommendations of Lane and others (1947). The sandstones and carbonates have been classified and described using the nomenclature of Folk (1959).

SD44SE/20 T.34 HAMILTON. Ground Level. 33.50

A.O.D. Static Water Level 24'05" A.O.D. (2-5-68)

		Depth in Feet	
Quaternary:		from	to
Soil:	Silt clay, A-B horizon, subangular, dark greyish-brown	0	1
	Mottled clay, very pale grey, micaceous	1	2.5
	Brown peaty clay, few mottles of yellowish brown	2.5	12
	Soft, silty clay, greyish	12	21
	Large boulder stone with coarse sand and gravel ¼" - 1½"	21	26
	Hard brown clay with gravel	26	30
	Grey sand and gravel, coarse-grained	30	36
	Brown and grey gravelly sand	36	77
	Coarse sand poorly sorted	77	87
	Red large and small gravel with sand, traces of red marl	87	100.6
Triassic:			
	Soft red sandstone rock, submature, mottled, fine-grained, orthoquartzite, light grey	100.6	134
	Hard sandstone, very fine-grained, light yellowish-brown	134	163

SD44SE/22 T.28 POPLAR GROVE. Ground Level. 38.25

A.O.D. Static Water Level 17' B.G.L. (2-5-68)

		Depth in Feet	
Quaternary:		from	to
Soil:	Silt clay, A-B horizon, sub-angular, very dark grey	0	1.6
	Soft clay, brown and light yellow-greyish with seams	1.6	20
	Light brown clay	20	40
	Greyish-brown clay, mottled	40	50
	Brown sands and gravels, medium-grained	50	55
	Hard packed small gravel in boulder clay	55	81
	Hard packed brown sandy clay	81	90
	Very dark brown sandy clay packed with pebbles ¼" x 1"	90	98
Triassic:			
	Very soft red sandstone medium-grained	98	105
	Hard brown sandstone submature, fine-grained	105	118.4
	Gravel fissure	118	119.6
	Hard brown sandstone	119	129

SD44 SE/E1 M.3 CATTERALL LAN. Ground Level 39+ A.O.D. Static Water Level unknown (20-6-69)

		Depth in Feet	
Quaternary:		from	to
Soil:	Silt clay	0	2
	Light brown clay with many leached calcareous nodules	2	8
	Sand soil, well sorted, fine to coarse sand with traces of fine gravel	8	16
	Dark brown clay	16	19
	Sandy clay	19	26
	Sandy clay with boulders	26	40
Triassic:			
	Soft red sandstone, medium-grained, submature	40	110
	Sandstone with thin marl bands	110	176
	Soft red sandstone	176	197
	Red Marl	197	202
	Soft red sandstone, fine-grained	202	205
	Hard red marl, very fine-grained	210	219
	Sandstone with marl beds	219	241
	Sandstone, light grey, fine-grained	241	248
	Sandstone bearing occasional marl beds	248	256
	Red marl, hard, fine-grained	256	258
	Sandstone, mature, light grey	258	263

	Depth in Feet	
	from	to
Red marl, very hard	263	296
Sandstone, hard, yellowish-brown	296	301
Sandstone with thin marl bands	301	326
Hard red marl	326	331
Sandstone bearing thin marl bands	331	350
Hard sandstone, very fine-grained	350	362
Red marl	362	364
Very hard sandstone	364	375

SD44 NE/13 T.46 MIDDLE HOLLY FORTON. Ground Level 92.05 A.O.D. Static Water Level 77.71 (3-7-70)

		Depth in Feet	
		from	to
Quaternary:			
	Made-up ground	0	8
	Small gravel bonded with grey clay	8	19
	Gravelly sand, greyish, poorly sorted	19	32
	Small hard packed grey and brown gravel (¼" - ½") bonded with clay	32	61
	Small grained hard light brown sand	61	71
Triassic:			
	Soft red sandstone, medium to fine-grained (Dip 5^{o} - 10^{o})	71	85
	Hard red-brown marl and marly sandstone	85	90
	Fine red-brown marly sandstone, some laminated sections (Dip 60^{o} - 70^{o})	90	95
	Fine grained marly sandstone (soft)	95	122
	Soft yellowish-grey marl	122	123
	Soft red-brown sandy marl with occasional yellow patches, and one piece of very hard light grey sandstone at about 125 feet	123	138

SD44 NE/14 T.36 Ground Level 64.77 A.O.D.

Static Water Level 57.13 A.O.D. B.G.L.

		Depth in Feet	
Quaternary:		from	to
	Black soil and turf	0	3
	Light brown sand and gravel (¼" - 2")	3	7
	Light ground sand and coarse gravel	7	20
Triassic:			
	Marl, hard, packed with small gravel and boulders	20	27
	Soft red sandstone rock, medium-grained	27	41
	Hard yellowish sandstone, fine-grained, mature	41	102

SD44 NE/15 T.37 FOWLERS HILL Ground Level
93.68 A.O.D. Static Water Level 41.0 A.O.D. (1-5-68)

		Depth in Feet	
Quaternary:		from	to
Soil:	Top soil and turf	0	1.2
	Stone rubble	1.2	3
	Sandy clay, bearing medium sand and fine-grained clay	3	11
	Gravelly sand, brown, poorly sorted	11	31
	Clay, brown with gravel lenses and black silty clay	31	34
	Firm brown clay	34	38
	Very hard dark brown clay	38	41
	Large boulder stone and gravel with medium-grained light-brown sand	41	52
Triassic:			
	Sandstone, hard, brown, medium to fine-grained	52	138

SD44 SE/23 T.50 TARNACRE Ground Level 29.63 A.O.D. Static Water Level 23.71 A.O.D. (10-5-71)

		Depth in Feet	
		from	to
Quaternary:			
Soil:	Silt clay with turf	0	2
	Clay, mottled, brown, fine-grained	2	4.6
	Soft grey clay, fine-grained	4.6	15
	Gravelly sand bearing fine-granitic gravel, coarse quartz sand	15	18
	Boulder clay, brown	18	36
	Grey washed gravel and coarse grey sand with boulder stone	36	47
	Gravel, hard packed in fine sand	47	52
	Clay, hard, brown	52	57
	Sand with granitic chip in bonded brown clay generally medium-grained	57	65
	Hard packed sandy clay with granitic chips	65	85
	Large stone and gravel	85	94
	Compact gravel	94	97
Triassic:			
	Brown and red sandstone, laminated with thin red marl bands; fine-grained medium hard	97	102
	Hard red laminated sandstone	102	107
	Soft red sandstone with thin layers of red marl	107	135

	Depth in Feet	
	from	to
Sandstone, coarse soft gritty, light brown	135	170
Sandstone, soft, brown medium to fine-grained	170	185

SD44 SE/13 T.41 Ground Level 41.20 A.O.D.

Static Water Level - influenced by pumping from adjacent borehole therefore not recorded

		Depth in Feet from	to
Quaternary:			
Soil:	Silt clay dark greyish-brown	0	0.9
	Clay, brown with boulders	0.9	2.4
	Sand, medium-grained brown	2.4	3
	Coarse sand	3	7
	Sand and gravel poorly sorted fine sand to medium gravel	7	10
	Clay yellowish-brown	10	11
	Sandy clay	11	34
Triassic:			
	Soft red sandstone	34	41.2
	Hard red sandstone, medium-grained	41.2	90
	Hard sandstone, yellowish-brown, fine-grained	90	153
	Red and grey marl, very fine-grained	153	154
	Red and grey sandstone, soft, poorly sorted	154	238
	Red sandstone, mature, fine-grained	238	268
	Red marl - very fine-grained	268	269
	Soft red sandstone	269	372
	Grey sandstone with marl, hard, very fine-grained	372	396

SD44 SE/E4 61/90 CHURCH TOWN Ground Level 32.4 A.O.D. Static Water Level 37.31 A.O.D.

		Depth in Feet	
		from	to
Quaternary:			
	Made up ground, ashes	0	10
	Clay, brown, fine-grained	10	17
	Clay, mottled, brown	17	22
	Clay, light brown, with gravel lenses	22	34
	Clay, dark brown, soft	34	49
	Sand and gravel with clay lenses	49	65
	Dark sandy clay	65	72.5
Triassic:			
	Soft red sandstone, mature, medium-grained with coal seams	72.5	87
	Red sandstone, hard	87	89
	Yellowish-grey sandstone, hard, fine-grained	89	99
	Red sandstone with marl, very fine-grained marl	99	144
	Yellowish-grey sandstone	144	165
	Hard red sandstone, mature, fine-grained, orthoquartzite	165	212
	Red/grey sandstone hard in places	212	234
	Yellowish-grey sandstone with fine-grained marl. Very hard	234	276

Description of Borehole Samples

SD44 NW/2 T.52 Ground Level 67 A.O.D.

Static Water Level 48.4 A.O.D.

		Depth in Feet	
Quaternary:		from	to
Soil:	Clayey silt, dark reddish-grey	0	1.6
Clayey silt:	Light reddish-brown	1.6	5
Silt:	Very pale brown	5	25
Silt:	Very calcareous	25	28
Very dark Clay:	Fine-grained	28	46
Clay:	Micaceous, medium dark-grey mottles of yellowish-brown, limonite	46	74
Clay:	Greyish, soft, fine-grained	74	85

SD44 NR/1 T.12 Ground Level 104.2 A.O.D.

Static Water Level unknown; test hole caved at 54 feet.

	Depth in Feet	
Quaternary:	from	to
Soil: Silty clay, granular dark-grey	0	4
Gravelly sand, bearing fine granitic gravel, moderately sorted fine sand to coarse gravel 20-26 per cent gravel	4	15
Clay: Very light grey, mottled yellowish-brown	15	25
Clay: Very light grey to light grey	25	45
Clayey Silts: Soft, medium-grained	45	92
Triassic:		
Sandstone: Yellowish-grey hard, very fine-grained	92	146

SD44 NE/10 L. Ground Level 97.4 A.O.D.

Static Water Level 56.4 A.O.D.

	Depth in Feet from	to
Quaternary:		
Soil: Silt clay: granular, dark grey to very dark grey	0	2.0
Silt Clay: Very pale brown	2.0	9
Slightly gravelly sand: fine granitic gravel, medium quartz sand	9	16
Clay: Very light grey to light grey, mottled	16	74
Clay: Dark grey, very fine-grained	74	127
Triassic:		
Sandstone with clear marl lenses fine-grained throughout	127	136
Sandstone yellowish-brown, hard	136	178
Sandstone with boulders, well-cemented	178	182
Hard sandstone, fine-grained, yellowish-brown	182	232

SD44 SE/14 Ground Level 92.6 A.O.D.

Static Water Level 27.4 A.O.D.

	Depth in Feet	
Quaternary:	from	to
Soil: Silt clay, granular, greyish-brown to dark-greyish brown	0	1
Sandy Silt Clay: Reddish-brown	1	7
Very gravelly sand: with claycast bearing granitic gravel and medium to coarse quartz sand, poorly sorted	7	14
Sandy Silt: Very pale brown, few fine mottles of yellowish-brown	14	35
Sandy Silt Clay: Very pale brown to pale brown	35	62
Gravelly sand, bearing fine granitic gravel, moderately to poorly sorted fine sand to coarse gravel	62	96
Triassic:		
Sandstone: red, soft, medium-grained	96	106
Sandstone: yellowish-red, medium-grained	106	145

SD44 SE/16 Ground Level 64.4 A.O.D.

Static Water Level 34.2 A.O.D.

	Depth in Feet from	to
Quaternary:		
Soil: Silty clay, dark grey to dark-reddish-brown	0	1.5
Silty Clay: Reddish-brown with traces of gravel and sand	1.5	9
Slightly sandy silt: pale brown, mottles of yellowish-brown	9	22
Slightly gravelly sand and interbedded clay: very coarse quartz sand	22	134
Triassic:		
Sandstone: Reddish, soft, fine-grained (wet)	134	147
Sandstone: Reddish-brown with medium quartz grains	147	195
Sandstone: Yellowish, very hard	195	201

APPENDIX 2

Chemical Analysis of Ground Water, the Fylde, Lancashire

Results in parts per million, except
where otherwise indicated

* denotes water samples collected from alluvial aquifers

** denotes water sample from sands and gravel aquifer

The rest of the samples were collected from the main Bunter Sandstone aquifer

TDS $>$ 800, samples are brackish

															CATIONS						ANIONS
Sample No.	Ca	Mg	Na	K	Fe	HCO_3	CO_3	SO_4	Cl	NO_3	pH	Temperature (°C.)	TDS (calculated)	Specific conductance μmhos cm. at 25° C.	Ca (epm)	Mg (epm)	Na + K (epm)	$HCO_3 + CO_3$ (epm)	SO_4 (epm)	Cl (epm)	Sum of Cations
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	45	5.5	34	2.4	0.0	201	0	23	18	0.0	6.7	12	247	350	2.2	0.5	1.6	3.3	0.5	0.5	4.3
2	130	15.0	54	5.1	0.5	378	0	145	35	0.0	6.6	12	630	890	6.5	1.2	2.4	6.2	3.0	0.9	10.1
3	106	16.0	29	4.3	0.2	352	0	97	13	8.8	6.7	12	499	715	5.3	1.3	1.4	5.7	2.0	0.3	8.0
4	67	5.2	24	4.9	0.0	185	0	50	13	52.0	6.6	11	352	510	3.3	0.4	1.1	3.0	1.0	0.4	4.8
5	85	10.0	20	2.7	1.6	344	0	38	15	0.0	7.0	10	370	560	3.4	0.8	3.4	4.4	0.5	2.7	7.6
6	97	5.3	74	4.9	1.2	391	0	98	5	0.9	6.9	11	525	800	4.8	0.4	3.3	6.4	2.0	0.1	8.5
7	76	11.0	37	3.6	8.0	222	0	125	11	0.0	6.8	11	426	620	3.8	1.0	1.7	3.6	2.6	0.3	6.5
8	95	8.6	28	3.2	1.8	273	0	95	8	2.6	6.8	11	390	580	4.7	0.7	1.3	4.5	2.0	0.2	6.7
9	93	12.0	45	4.4	0.2	229	0	150	30	31.0	6.5	11	511	720	4.6	1.0	2.1	3.8	3.1	0.9	7.7
10	76	7.2	44	1.7	0.2	393	0	10	8	4.4	7.0	11	380	585	4.3	0.6	1.9	6.4	0.2	0.2	6.8
11	290	54.0	158	9.4	1.9	332	0	883	84	15.0	6.8	12	780	2370	14.5	4.4	7.1	5.2	17.8	2.4	2.6
12	123	6.2	47	1.9	0.1	361	0	28	76	176.0	7.1	12	662	1010	6.1	0.5	2.0	5.9	0.6	2.1	8.6
13	50	8.2	26	4.0	0.0	217	0	27	12	1.3	6.8	12	281	410	2.5	0.7	1.2	3.6	0.5	0.3	4.4
14	66	14.0	27	3.4	0.0	287	0	29	25	40.0	6.9	10	381	575	3.3	1.1	1.2	4.7	0.2	0.7	5.6
15	97	14.0	15	2.4	0.0	374	0	21	10	0.0	7.1	10	395	600	4.8	1.2	0.7	6.1	0.4	0.3	6.7
16	86	9.1	17	3.6	0.0	304	0	29	7	4.4	6.9	13	368	545	4.3	0.7	0.8	5.0	0.6	0.2	5.8
17	24	3.8	13	4.2	0.0	120	0	8	5	3.1	6.6	12	157	205	1.2	0.3	0.7	2.0	0.1	0.1	2.2
18	54	8.6	23	4.2	0.0	224	0	35	8	5.7	6.8	12	285	422	2.7	0.7	1.1	3.7	0.7	0.2	4.5
19	96	16.0	48	5.3	0.0	332	0	130	13	8.4	7.1	12	543	725	4.8	1.3	2.3	5.4	2.7	0.4	8.4
20	60	10.0	73	4.1	0.0	229	0	51	81	2.6	6.8	12	429	695	3.0	0.8	3.3	3.7	1.1	2.3	7.1
21	65	10.0	30	4.0	0.3	266	0	23	16	6.2	6.9	12	333	505	3.2	0.8	1.4	4.4	0.5	0.5	5.4
22	53	8.2	25	3.8	0.2	227	0	24	10	4.4	6.8	12	285	437	2.6	0.7	1.2	3.7	0.5	0.3	4.5
23	50	8.6	26	4.0	0.7	210	0	36	12	1.8	6.8	11	275	425	2.5	0.7	1.2	3.4	0.7	0.3	4.4
24	38	7.2	19	4.4	0.0	168	0	21	8	3.5	6.7	11	217	315	1.9	0.6	0.9	2.8	0.4	0.2	3.4

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
25	55	9.6	22	4.0	0.3	222	0	39	11	4.0	6.9	11	290	439	2.7	0.8	1.2	3.6	0.8	0.3	4.7
26	41	7.2	22	4.2	0.0	188	0	21	7	2.2	6.8	11	234	345	2.1	0.5	1.1	3.1	0.4	0.2	3.7
27*	69	12.0	30	3.4	0.2	259	0	41	26	4.4	6.9	11	349	540	3.4	1.0	1.4	4.2	0.9	0.7	5.8
28*	81	4.8	58	3.5	2.0	332	0	64	12	0.0	7.0	11	426	635	4.0	0.4	2.6	5.4	1.3	0.3	7.0
29	111	11.0	115	6.4	1.5	461	0	150	34	0.0	6.7	11	701	975	5.5	0.9	5.2	7.6	3.1	1.0	11.6
30	134	6.2	25	4.8	0.5	403	0	39	23	44.0	6.8	10	521	830	6.5	0.5	1.2	6.6	0.8	0.7	8.2
31	102	3.8	41	3.6	1.6	378	0	23	18	48.0	7.0	13	481	795	5.1	0.3	1.8	6.2	0.5	0.5	7.2
32	64	6.7	27	3.2	0.0	268	0	10	20	18.0	6.8	13	324	493	3.2	0.6	1.3	4.4	0.2	0.5	5.1
33	36	5.8	11	3.9	0.0	122	0	23	7	27.0	6.6	14	208	300	1.8	0.4	0.5	2.0	0.5	0.2	2.7
34	43	10.0	17	4.6	0.0	112	0	48	32	92.0	6.4	13	316	435	2.1	0.8	0.8	1.8	1.0	0.9	3.7
35	80	10.0	15	2.6	0.6	286	0	39	6	2.6	7.0	13	347	540	4.0	0.8	0.7	4.7	0.8	0.1	5.6
36	94	9.6	13	2.8	1.4	334	0	41	3	0.9	6.8	13	348	550	4.7	0.8	0.6	5.4	0.8	0.1	6.1
37	97	14.0	11	2.0	0.0	337	0	29	11	6.2	7.0	12	375	605	4.8	1.1	0.5	5.5	0.6	0.3	6.4
38	100	8.2	63	6.5	0.3	403	0	55	33	48.0	7.1	12	533	850	5.0	0.7	2.9	6.6	1.1	0.9	8.6
39	192	18.0	26	2.8	5.0	385	0	280	13	0.0	6.8	11	776	1070	9.6	1.5	1.2	6.3	5.8	0.3	12.3
40	42	15.0	231	5.2	1.2	342	0	88	212	0.0	7.0	12	804	1320	2.1	1.2	10.1	5.6	1.8	6.0	13.4
41	71	8.2	86	.9	1.8	409	0	47	11	6.6	7.1	11	465	690	3.5	0.7	3.8	6.7	1.0	0.3	8.0
42	94	6.2	18	2.8	1.8	286	0	93	4	0.0	6.6	12	390	585	4.7	0.5	0.9	4.7	1.9	0.1	6.1
43	160	54.0	3370	25.0	0.7	371	0	775	4956	0.9	7.2	11	9500	13000	8.0	6.9	147.2	6.1	16.1	139.7	162.1
44	29	13.0	25	3.0	3.2	90	0	86	17	0.0	6.3	12	276	400	1.4	1.1	1.2	1.5	1.8	0.5	3.7
45	114	0.0	21	3.5	3.2	281	0	92	7	0.4	6.8	13	430	670	5.7	0	1.0	4.6	1.9	0.2	6.7
46	34	6.2	36	2.8	0.1	142	0	18	42	4.8	6.5	14	252	395	1.7	0.5	1.7	2.3	0.4	1.2	3.9
47	84	10.0	27	2.3	1.8	204	0	140	10	0.0	6.5	12	434	605	4.2	0.8	1.3	3.3	2.9	0.3	6.3
48	70	8.6	23	1.5	0.6	274	0	32	7	0.0	7.1	12	315	480	3.5	0.7	1.2	4.5	0.7	0.2	5.4
49	40	5.8	33	2.1	0.0	159	0	43	13	31.0	6.7	12	276	405	2.0	0.5	1.5	2.6	0.9	0.4	4.0
50	114	8.6	74	1.4	0.8	381	0	146	15	22.0	7.0	12	622	895	5.7	0.7	3.2	6.2	3.0	0.4	9.6
51**	88	8.6	29	2.7	0.5	320	0	50	12	16.0	6.7	11	402	640	4.4	0.7	1.4	5.2	1.0	0.3	6.5
52	92	12.0	98	3.6	1.8	337	0	115	92	0.0	7.1	11	609	970	4.6	1.0	4.4	5.5	2.4	2.4	10.00

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
53	296	54.0	316	7.7	4.0	268	0	900	345	0.0	7.2	11	2038	2780	14.7	4.4	13.9	4.4	18.7	9.7	33.0
54	141	16.0	47	2.3	0.0	339	0	210	16	31.0	7.0	12	678	905	7.0	1.3	2.1	5.6	4.3	0.5	10.4
55	46	9.8	19	3.5	0.0	198	0	27	7	0.0	6.8	12	241	365	2.3	0.8	0.9	3.2	0.6	0.2	4.0
56	129	15.0	25	2.7	0.0	317	0	160	15	15.0	7.0	12	556	795	6.4	1.2	1.2	5.2	3.3	0.4	8.8
57	26	3.8	16	3.7	0.0	130	0	9	4	1.8	6.6	12	169	230	1.3	0.3	0.8	2.1	0.2	0.1	2.4
58	42	8.2	23	4.6	0.0	178	0	5	9	5.7	6.7	12	248	375	2.1	0.7	1.1	2.9	0.7	0.3	3.9
59	88	12.0	21	2.9	0.2	324	0	39	10	7.0	7.0	14	383	570	4.4	1.0	1.0	5.3	0.8	0.3	6.4
60	58	9.1	25	3.6	0	222	0	38	15	5.3	6.7	14	302	460	2.9	0.7	1.2	3.6	0.8	0.4	4.8

Analysis by Lancashire and Birmingham Water Authorities' Analysts using laboratory methods

APPENDIX 3

Drawdown in Pumping Wells

Drawdown in Pumping Well
(Constant Rate-Test)
April, 1977

Drawdown in Pumping Well - Pump Test- April, 1977

Date	Time (hrs.mins.)	Elapsed time since pumping begun (mins.)	Depth to Water (feet)	Drawdown corrected for barometric pressure	Q = discharge rate (igpm)	B.P. = barometric pressure
1	2	3	4	5	6	7
March 25/77	2.00 pm		24.86			
	4.00		24.84			
	6.00		24.83			
March 31/77	9.00 am		24.76			
	9.30		24.75			
	10.00		24.75			
April 19/77	7.00 am		24.68			
	7.30		24.68			
	8.00		24.68			
	8.30		24.68			
	9.00	0	24.68	0.00	60	
		1	24.94	0.26		
		2	25.18	0.5		
		3	25.37	0.69		
		4	25.54	0.86		
		5	25.74	1.06		807.9

1	2	3	4	5	6	7
		6	25.87	1.19	60 igpm	
		7	26.00	1.32		
		8	26.1	1.42		
		9	26.21	1.53		
	9.10	10	26.29	1.61		
		15	26.66	1.98		
		20	26.89	2.21		
		25	27.12	2.44		
	9.30	30	27.24	2.56		
		40	27.29	2.61		
		50	27.35	2.67		
	10.00	60	27.39	2.71		
		70	27.48	2.80		808.4
		80	27.55	2.87		
		90	27.59	2.91		
	11.00	120	27.66	2.98		808.4
		140	27.68	3.00		
		160	27.74	3.06	60	
	12.00	180	27.76	3.08		807.8
		200	27.78	3.10		
		220	27.82	3.14		

1	2	3	4	5	6	7
April 20/77	1.00 pm	240	27.83	3.15		807.7
		260	27.89	3.21		
		300	27.89	3.21		807.5
		320	27.91	3.23		
		340	27.93	3.25		
	3.00	360	27.95	3.27		807.5
		390	27.95	3.27		
		420	27.96	3.28		807.6
		440	27.97	3.27		
	5.00	480	27.98	3.30		807.9
		540	28.02	3.34		807.8
	7.00	600	28.07	3.39		808.0
		660	28.1	3.42		807.9
	9.00	720	28.1	3.42	60	808.2
		780	28.12	3.44		809.6
	11.00	840	28.12	3.44		809.2
	Midnight	960	28.2	3.52		808.9
April 21/77	3.00	1080	28.29	3.61		809
	5.00	1200	28.42	3.84		808.6
	7.00	1320	28.66	3.98		808.5
	9.00	1440	28.74	4.07		808.3
	11.00	1560	28.73	4.06		808.2
	3.00	1800	28.92	4.25		806.9
	7.00	2040	29.04	4.36		804.4

1	2	3	4	5	6	7
	11.00	2280	29.08	4.40		802.2
	3.00	2520	29.08	4.40		800.5
	7.00	2760	29.09	4.41		797.9
	11.00	2900	29.08	4.40		794.1
	5.00	3260	29.1	4.43		792.4
	9.00	3500	29.11	4.44		800.2
	12.00	3680	29.11	4.44		803.1

Drawdown in Pumping Well
(Step-Test)
March, 1977

Drawdown in Pumping Well - Step Test, March, 1977

Date	Time (hrs.mins)	Elapsed time since pumping begun (mins)	Depth to Water (feet)	Drawdown (feet)	Q = discharge rate (gpm)
1	2	3	4	5	6
March 23/77	10.00	0	24.05	0	20
		1	25.97	1.92	
		2	26.11	2.06	
		3	26.13	2.08	
		4	26.13	2.08	
		5	26.11	2.06	
		6	26.01	1.96	
		7	26.00	1.95	
		8	26.01	1.96	
		9	26.03	1.98	
		10	26.01	1.96	
		15	26.09	2.04	20
		20	26.09	2.04	

1	2	3	4	5	6
		25	26.06	2.01	
	10.30	30	26.05	2.00	
		40	26.06	2.01	
		50	26.08	2.03	
	11.00	60	26.06	2.01	
		61	28.80	4.75	30
		62	28.65	4.60	
		63	28.65	4.60	
		64	28.66	4.61	
		65	28.65	4.60	
		66	28.65	4.60	
		67	28.67	4.62	
		68	-	-	
		69	28.69	4.64	
	11.10	70	28.70	4.65	
		75	28.83	4.78	30
		80	28.84	4.79	
		85	28.84	4.79	

1	2	3	4	5	6
	11.30	90	28.84	4.79	30
		100	28.84	4.79	
		110	28.83	4.78	
	12.00	120	28.81	4.76	45
		121	31.89	7.84	
		122	32.19	8.14	
		123	32.30	8.25	
		124	32.35	8.30	
		125	32.39	8.34	
		126	32.41	8.36	
		127	32.41	8.36	
		128	32.42	8.37	
		129	32.42	8.37	
	12.10	130	32.42	8.37	
		135	32.69	8.64	
		140	32.77	8.72	45
	12.30	150	32.80	8.75	
		160	32.82	8.77	
		170	32.83	8.78	
	1.00 pm	180	32.85	8.80	Recovery begins

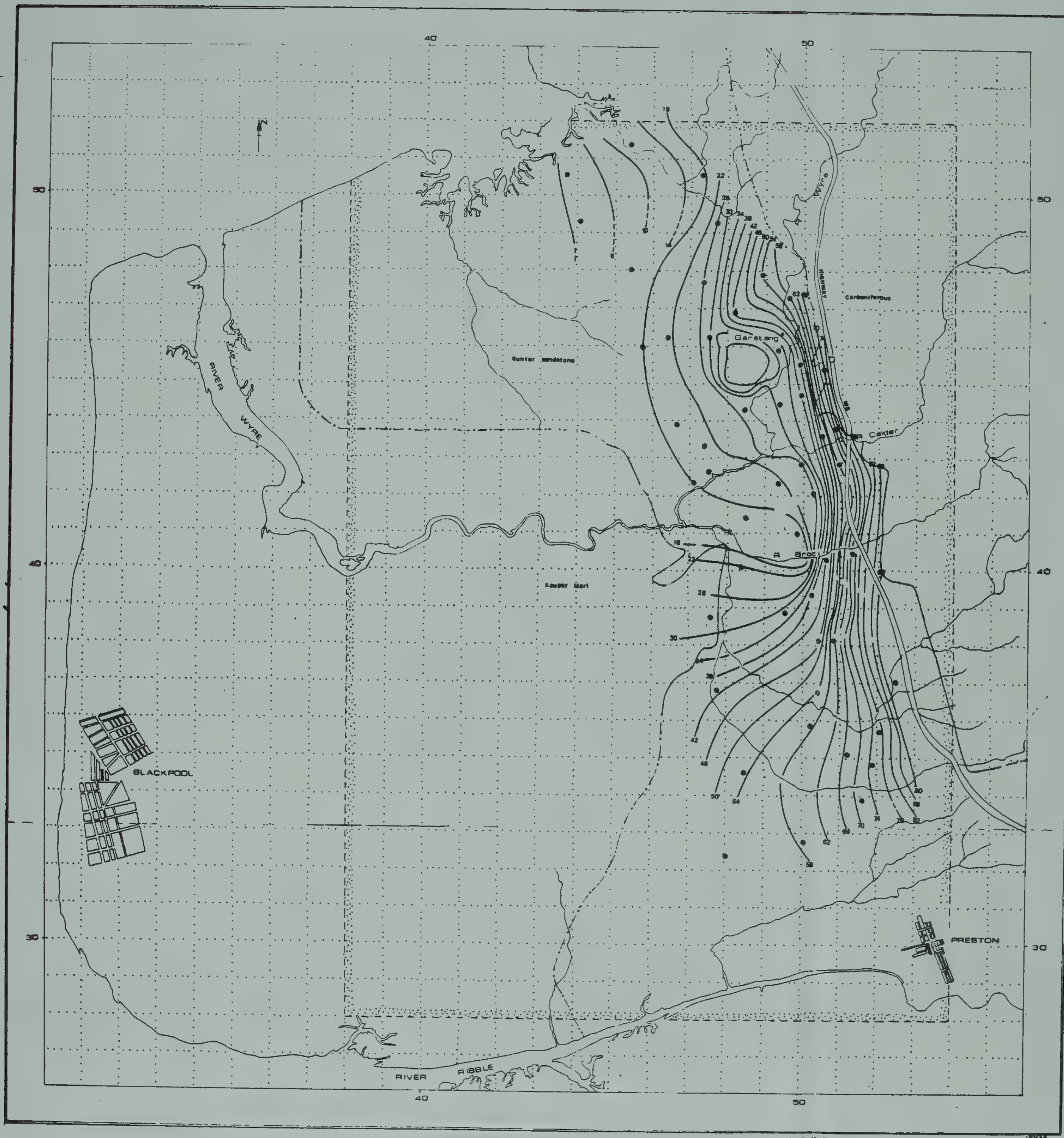
APPENDIX 4

Recommended Limits of Chemical Constituents in Drinking Water

Recommended Limits of Chemical Constituents in Drinking Water

Constituent	Recommended limit (ppm) (U.S. Public Health Service	Maximum recommended limits (mg/l) in Great Britain*
Total Solids	500	1500
Sulphate	250 (as SO_4)	250
Chloride	250	200
Iron	0.3 (fe + Mn)	0.3
Nitrate	45 (as NO_3)	50
Magnesium	125	50
Fluoride	1.5	.7
Soda (Na_2CO_3)	Not stated	Not stated

*Source: The Draft E.E.C. Drinking Water Standards - Official Journal of the European Communities No. C 214/7, 1976.



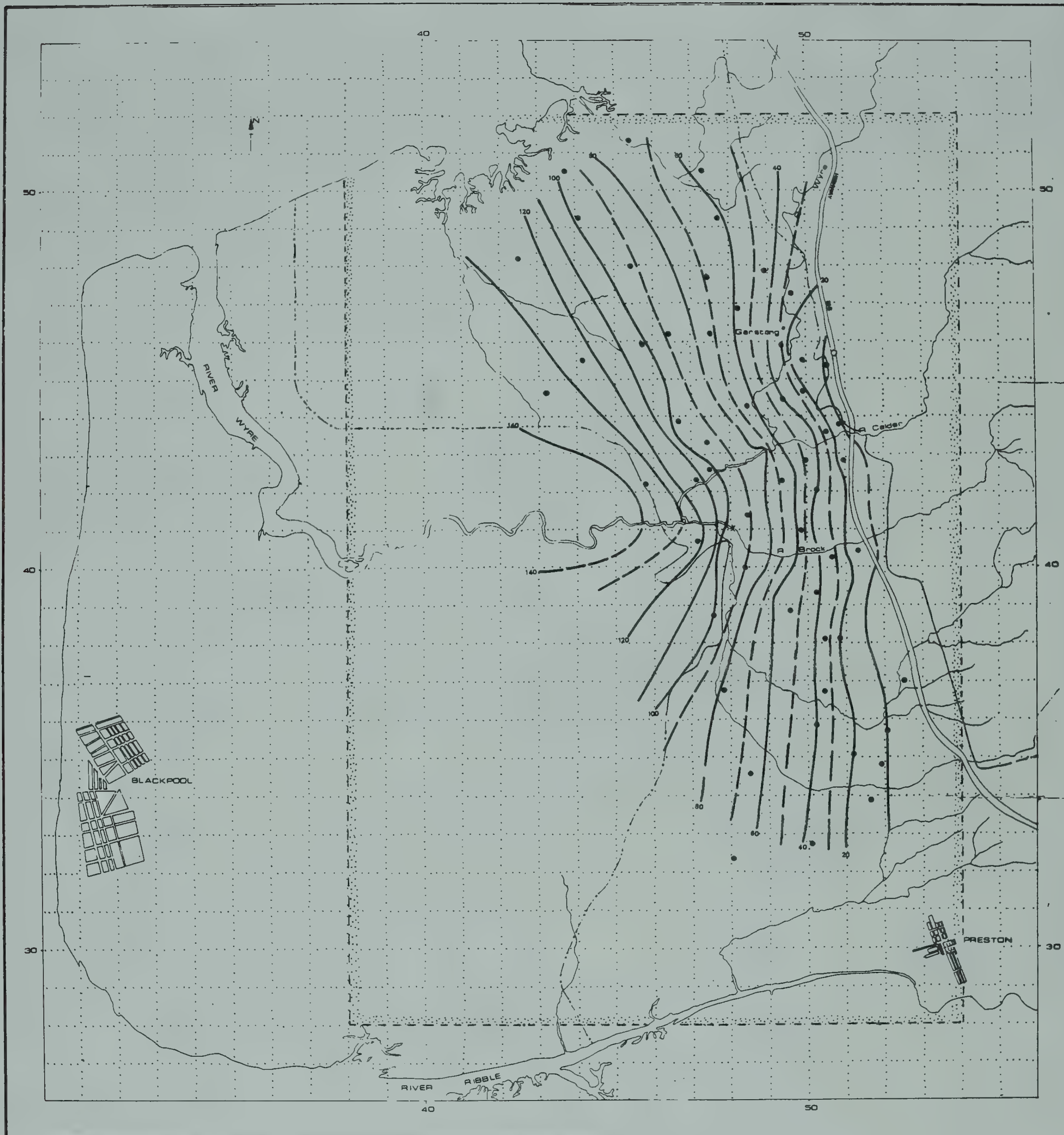
Enclosure 1 MAP SHOWING STATIC WATER LEVELS

LEGEND

Static water level contour (Contour interval 4 feet)

Control point

JEKM



Enclosure 2 GENERALISED ISOPACH MAP of the DRIFT

2 1 0 1 2 3 Kilometres
1 0 Miles 1 2

LEGEND

Drift thickness in feet 40

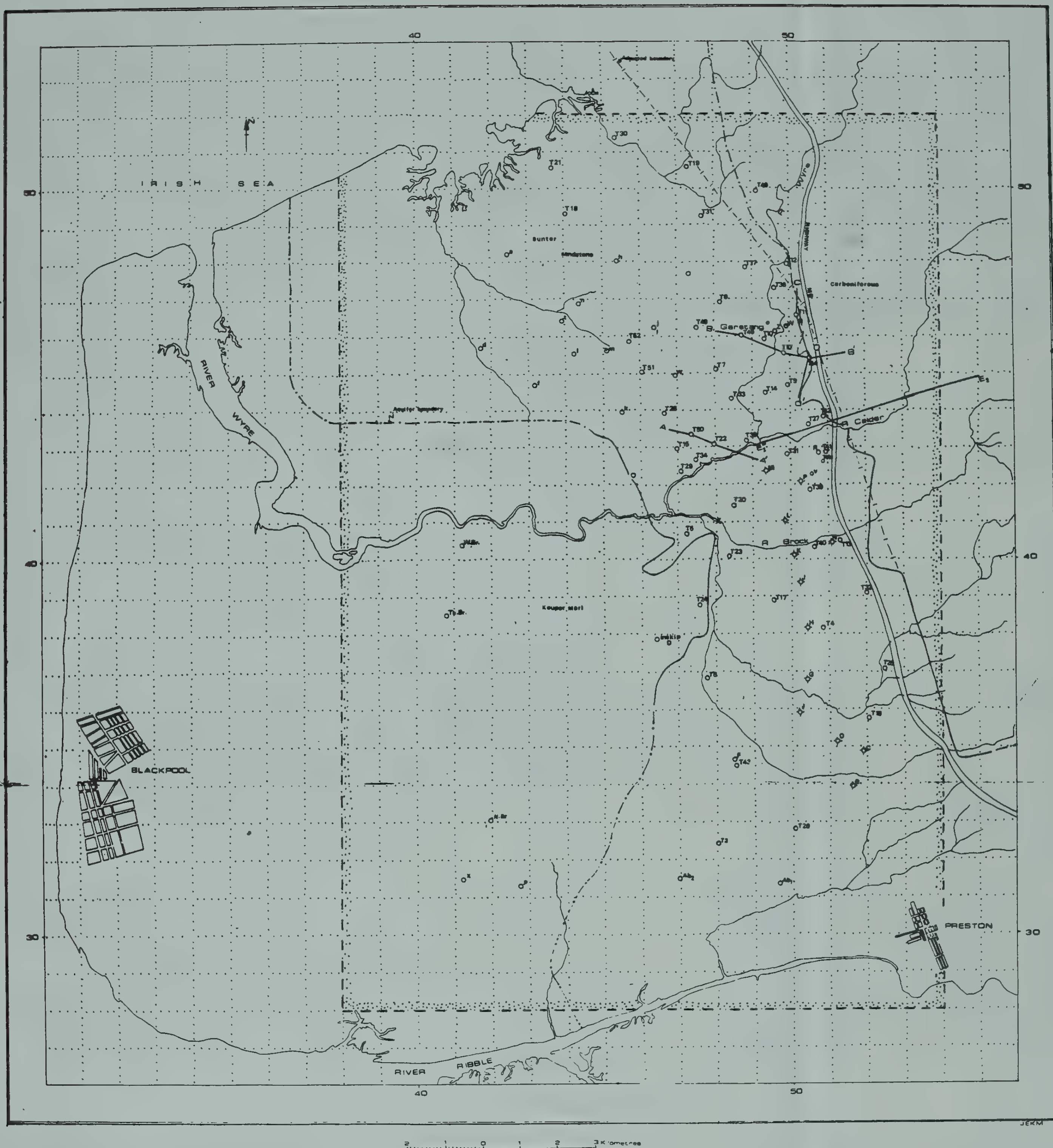
Control point . . . . ●

Enclosure 3 DEPTH TO BEDROCK MAP

LEGEND

Bedrock contour
definite 60
assumed 110
(Contour interval 10 feet)

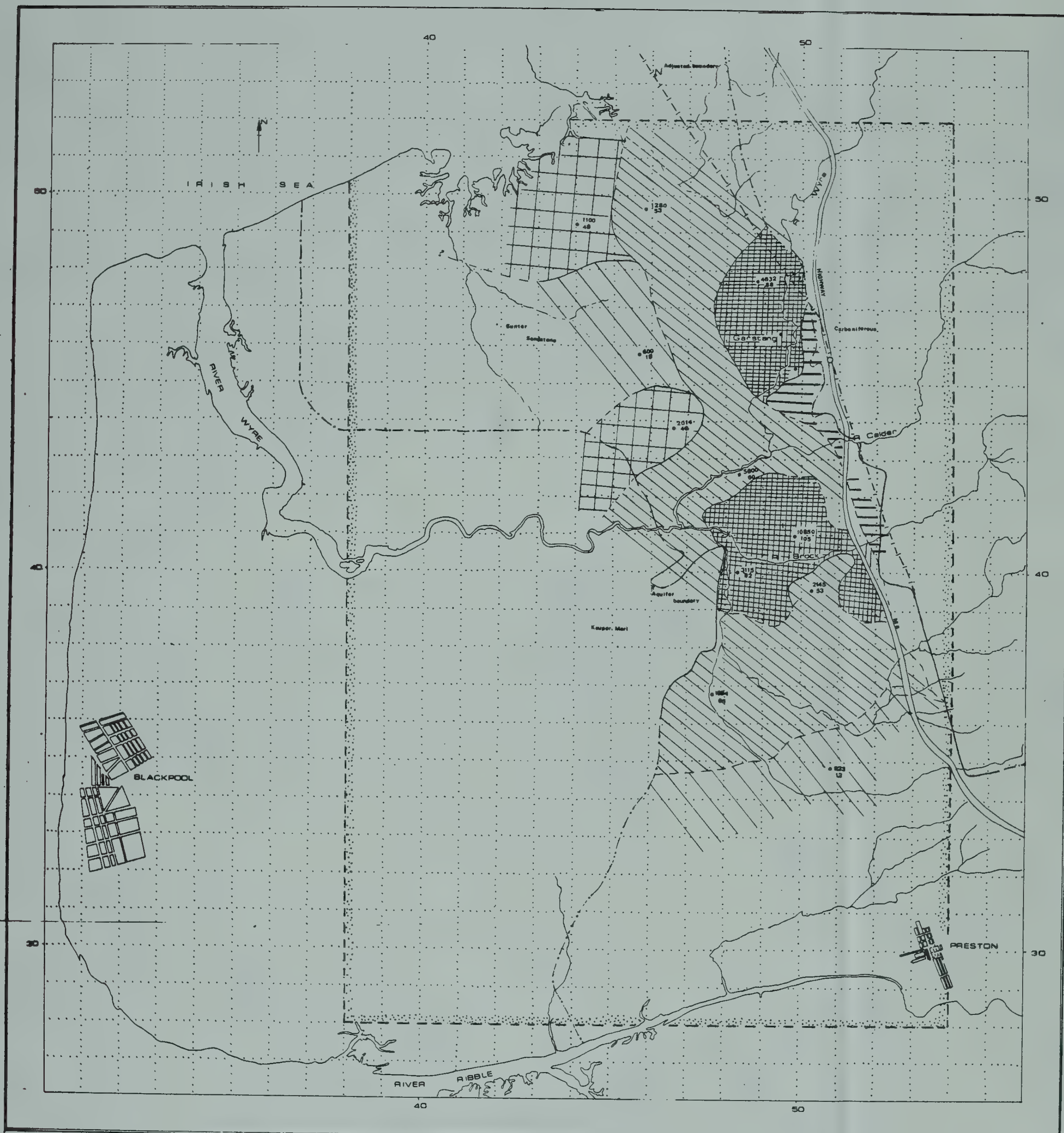
Control point . . . .



Enclosure 4 MAP SHOWING LOCATIONS of OBSERVATION POINTS, GEOLOGIC and HYDRAULIC CROSS - SECTIONS.

LEGEND

Fylde Well No. E .... (Multi-well sites)
Fylde Well No. T41 .... (Single well sites)
Geologic cross section B——B'
Hydraulic cross section .... E_2——E_2



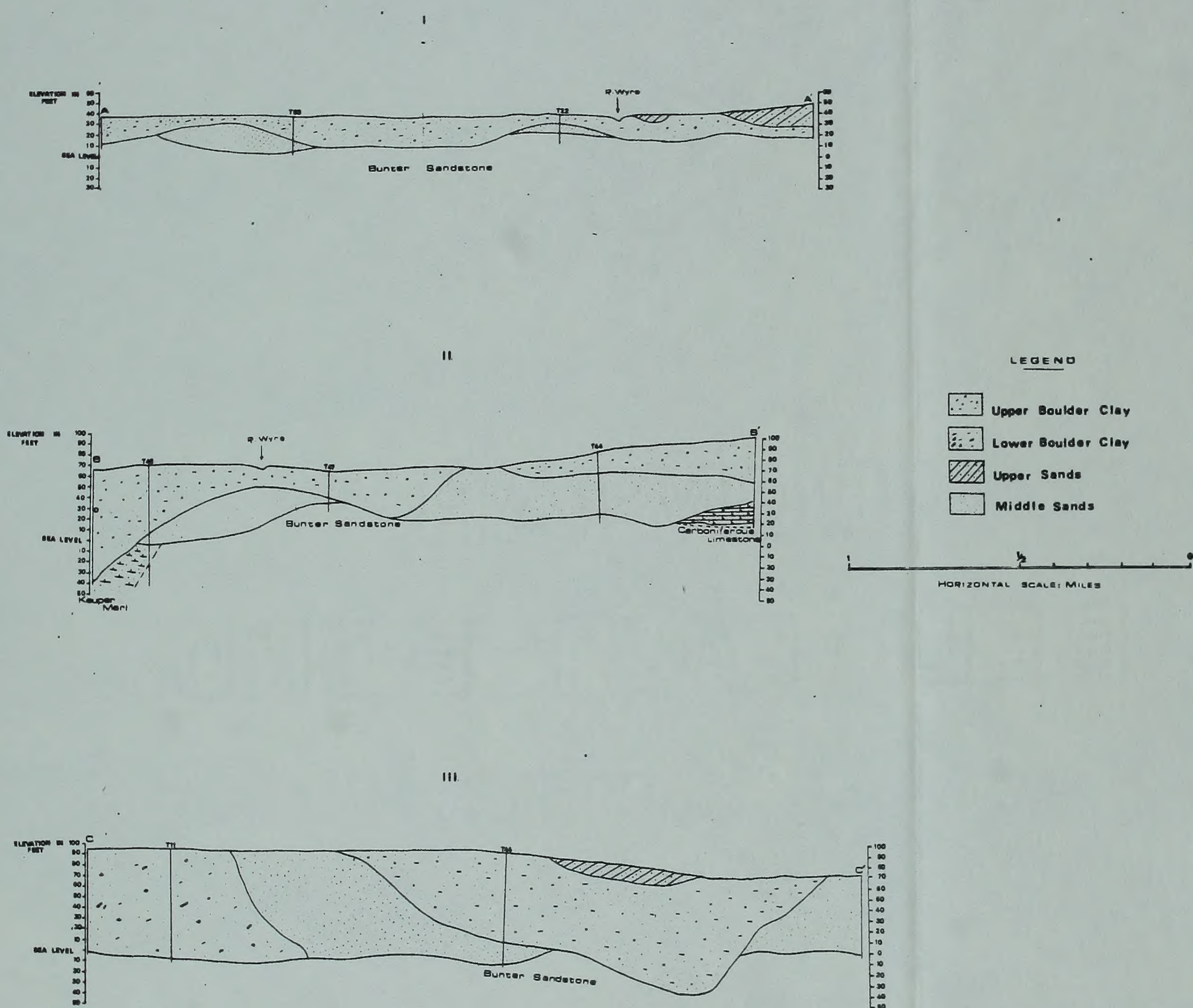
Enclosure 5

MAP SHOWING GROUND WATER PROBABILITY IN THE FYLDE AREA, LANCASHIRE.

LEGEND

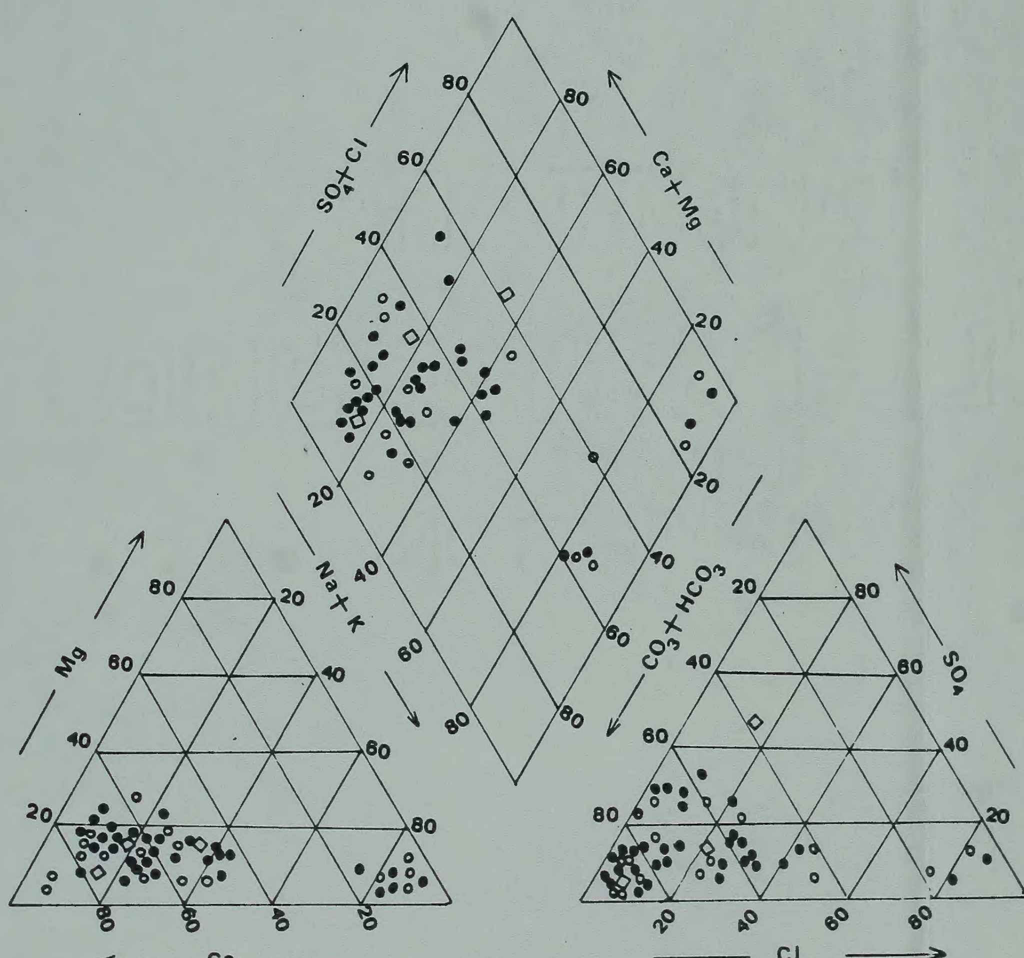
Probable yield to wells
[imperial gallons per minute]

- Less than 10
- 10 – 25
- 25 – 50
- 50 – 75
- More than 75
- Water well or test well
- 823 — Transmissibility or apparent transmissibility in imperial gallons per day per foot
- 12 — Calculated 20 year safe yield in gpm



Enclosure 6: SECTIONS THROUGH THE DRIFT

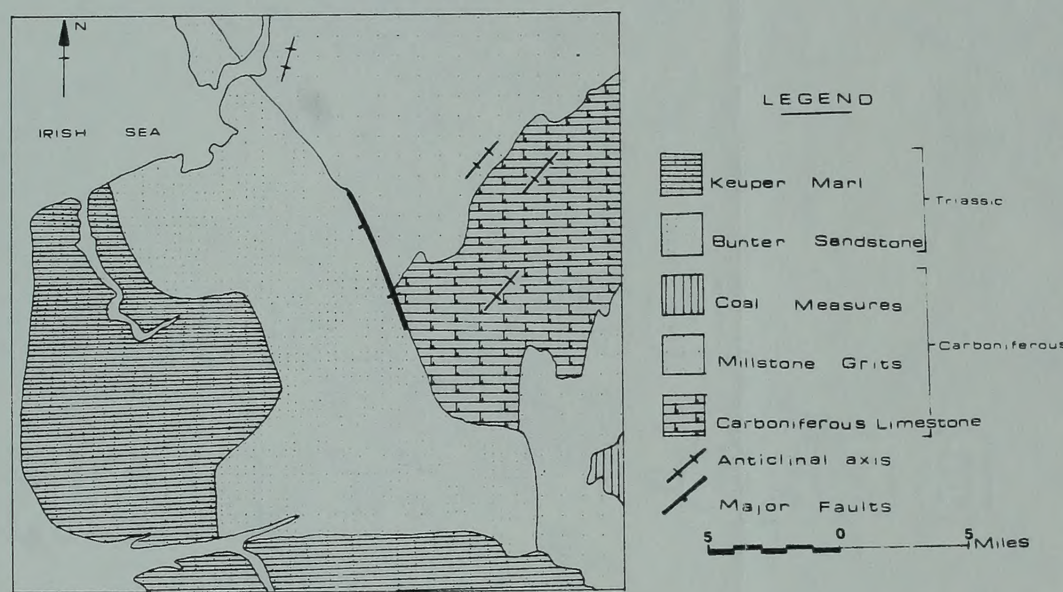
Enclosure 7



TRILINEAR DIAGRAM SHOWING THE CHEMICAL CHARACTERISTICS OF GROUND WATER IN THE FYLDE AREA, LANCASHIRE

51 wells (1976 - 77)

J·E·K·M



Enclosure 8 GENERALISED GEOLOGY OF THE FYLDE AND SURROUNDING AREAS

/Slightly modified after Trotter.1954 /